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DOSES RESULTING FROM INTRUSION INTO URANIUM TAILINGS AREAS

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ABSTRACT

In the future, it is conceivable that institutional controls of uranium tailings areas may cease to exist and individuals may intrude into these areas unaware of the potential radiation hazards. The objective of this study was to estimate the potential doses to the intruders for a comprehensive set of intrusion scenarios. Reference tailings areas in the Elliot Lake region of northern Ontario and in northern Saskatchewan were developed to the extent required to calculate radiation exposures. The intrusion scenarios for which dose calculations were performed, were categorized into the following classes: habitation of the tailings, agricultural activities, construction activities, and recreational activities. Realistic exposure conditions were specified and annual doses were calculated by applying standard dose conversion factors. The exposure estimates demonstrated that the annual doses resulting from recreational activities and from construction activities would be generally small, less than twenty millisieverts, while the habitational and agricultural activities could hypothetically result in doses of several hundred millisieverts. However, the probability of occurrence of these latter classes of scenarios is considered to be much lower than scenarios involving either construction or recreational activities.

RÉSUMÉ

À l'avenir, il se peut qu'il n'y ait plus de contrôles institutionnels des endroits où se trouvent des résidus d'uranium et que des personnes puissent entrer par inadvertance dans ces lieux sans se rendre compte des dangers possibles d'irradiation. La présente étude vise à évaluer, pour toute une série de situations possibles, les doses que pourraient recevoir les personnes qui y seraient entrées sans être conscientes des dangers. On a défini des aires de résidus de référence dans la région d'Elliot Lake au nord de l'Ontario et dans le nord de la Saskatchewan, de façon à nous permettre de calculer les radioexpositions. Les situations possibles d'entrée par inadvertance pour lesquelles des calculs ont été effectués ont été classées selon les catégories suivantes : l'habitation sur les lieux où se trouvent les résidus d'uranium, les activités agricoles, les activités de construction et les activités de loisir. Des conditions d'exposition réalistes sont précisées et des doses annuelles sont calculées au moyen de facteurs types de conversion de doses. Les estimations d'irradiation révèlent que les doses annuelles attribuables aux activités de loisir et de construction sont d'ordinaire minimes, à savoir moins de 20 mSv, tandis que celles qui sont attribuables à l'habitation sur les lieux où se trouvent les résidus et aux activités agricoles seraient en théorie de l'ordre de plusieurs centaines de millisieverts. Toutefois, on estime qu'il y a beaucoup moins de chances que se présentent ces deux dernières catégories de situations que celles touchant les activités de construction et de loisir.

DISCLAIMER

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0. EXECUTIVE SUMMARY

The objective of this report is to estimate the doses resulting from a comrehensive set of intrusion scenarios into tailings areas for which administrative contols have broken down. The study was undertaken by W&W Radiological and Environmental Consultant Services, Inc. under a contract awarded by the Atomic Energy Control Board.

As a basis for calculating the doses, two reference tailings sites were developed for the Elliot Lake mining region and the northern Saskatchewan mining region. The characteristics of these sites were based primarily on those of the Nordic area on the Pre-Cambrian shield in the Elliot Lake region, and the Rabbit Lake tailings area on the Athabaska sandstone in northern Saskatchewan. The tailings areas were modelled to the extent required to calculate radiation fields and radionuclide concentrations. A standard methodology to calculate radiation doses arising from each exposure pathway was applied. This methodology attempted to take into account the significant variables in the exposure conditions. The doses arising from each scenario are summarized in Table 0.1 for the Elliot Lake reference site and in Table 0.2 for the northern Saskatchewan reference site. The calculations demonstrate the following:

- Doses arising from intrusions for recreational activities on the tailings are relatively low, typically less than 10 mSv. Based on previous experience in both uranium and non-uranium tailings areas, intrusions for the purpose of engaging in a recreational activity are believed to be the most likely.

- Tailings areas have been used as a source of construction materials. The doses resulting from construction scenarios are also relatively low, less than 20 mSv.

- Habitational and agricultural intrusions are considered to be the least probable owing to the very unfavourable conditions on the tailings for these activities. These intrusions, however, if effected, would result in relatively high doses, up to several hundred millisieverts.

Dose calculations were performed for selected combination of intrusion scenarios. These dose estimates are given in Table 0.3. As these combination of scenarios are highly unlikely, these dose estimates are provided solely for the sake of illustration.

The differences in tailings management concepts, the physical and chemical properties of the ore, and the uncertainties with respect to final concepts for waste management particularly in northern Saskatchewan are such, that the development of a generic tailings site for Canada is not considered feasible. For sites based on the land/shallow water management concept, the dose assessments pertaining to the Elliot Lake reference tailings site and the northern Saskatchewan tailings site provide reasonable estimates of the doses potentially received by intruders into these areas. Moreover, the methodology used in this study for calculating doses could be applied

to a wide range of tailings management concepts, provided that a sufficiently complete data base on tailings characteristics is available.

TABLE 0.1

ANNUAL DOSES RECEIVED BY INTRUDER INTO ELLIOT LAKE REFERENCE TAILINGS SITE

SCENARIO	EFFECTIVE DOSE EQUIVALENT (mSv)			
	DIRECT GAMMA	INHALED PARTICLATES	INHALED RN DAUGHTERS	INGESTED RADIOACTIVITY
HUT	20	0.2	360	
HOUSE	10	0.2	360	
WELL				
(HIGH ACID)				180
(LOW ACID)				50
GARDENING	0.6		neg.	2
CATTLE RAISING	0.2		neg.	20
ROAD	2	0.4	neg.	
EXCAVATION	2	1.0	neg.	
CAMPING	3	0.02	neg.	
RACING	0.03	0.06	neg.	
SWIMMING	0.006			

neg.-- negligible

TABLE 0.2

ANNUAL DOSES RECEIVED BY INTRUDER INTO NORTHERN SASKATCHEWAN TAILINGS SITE

SCENARIO	EFFECTIVE DOSE EQUIVALENT (mSv) DIRECT GAMMA	INHALED PARTICLATES	INHALED RN DAUGHTERS	INGESTED RADIOACTIVITY
HUT	120	0.2	170	
HOUSE	50	0.2	170	
WELL				N/A
GARDENING	3		neg.	10
CATTLE RAISING	0.9		neg.	70
ROAD	9	0.07	neg.	
EXCAVATION	9	2	neg.	
CAMPING	20	0.02	neg.	
RACING	0.2	0.008	neg.	
SWIMMING	0.2			

N/A -- No data available.
neg. -- negligible

TABLE 0.3

ANNUAL DOSES RECEIVED BY INTRUDER PERFORMING VARIOUS COMBINATIONS OF ACTIVITIES ON TAILINGS SITES

ELLIOT LAKE REFERENCE TAILINGS AREA

SCENARIO COMBINATIONS	EFFECTIVE DOSE EQUIVALENT (mSv) DIRECT GAMMA	INHALED PARTICLATES	INHALED RN DAUGHTERS	INGESTED RADIOACTIVITY
INHABITANCY - 1	20	0.2	360	180
INHABITANCY - 2	20	0.2	360	50
AGRICULTURE	1			18
CONSTRUCTION	3	1		
RECREATION	3	1		

NORTHERN SASKATCHEWAN REFERENCE TAILINGS AREA

SCENARIO COMBINATIONS	EFFECTIVE DOSE EQUIVALENT (mSv) DIRECT GAMMA	INHALED PARTICLATES	INHALED RN DAUGHTERS	INGESTED RADIOACTIVITY
INHABITANCY - 2	120	0.2	170	10
AGRICULTURE	4			80
CONSTRUCTION	20	2		
RECREATION	20	0.3		

CODE OF SCENARIO COMBINATIONS:

INHABITANCY - 1 . Intruder inhabits hut situated on the tailings and obtains potable water from well sunk into the tailings.
INHABITANCY - 2. Intruder inhabits hut situated on the tailings and consumes produce grown on the tailings.
AGRICULTURE. Intruder raises produce and beef cattle on tailings.
RECREATION - Intruder camps and engages in sport racing on the tailings. In addition, intruder swims in contaminated tailings pond.

1.0 INTRODUCTION

1.1 REPORT BACKGROUND

A truly "walk-away" concept for the disposal of uranium mill wastes has not yet been developed. Accordingly, institutional controls are required to limit access to the uranium tailings areas. In the future, however, such controls may fail or cease to exist, and individuals may come into contact with the tailings and consequently receive radiation exposures. This report estimates the doses to such individuals for a comprehensive set of intrusion scenarios.

1.2 SCOPE

The study includes:

-- The analyses of all credible intrusion scenarios based on realistic assumptions of human behaviour and on current technology.
-- Calculations of the magnitudes of radiation fields and of the releases of radioactivity based on current tailings management practices.
-- Specification of the reference tailings areas to the extent required to determine the radiological conditions.
-- Calculated estimates of radiation doses to the intruders.

The following are considered outside of the scope of the study:

-- Determination of the detriment to human health arising from the exposure to toxic chemicals.
-- Calculation of radiation exposures that result from tailings materials that have been transported away from the tailings area as a result of the initial intrusion. For example, whilst the doses to the intruder excavating tailing material are determined in this study, the doses resulting from the use of the tailings materials remote from the original tailings area is considered outside the scope of this study.
-- Collective population radiation doses.

1.3 DOSE ESTIMATION METHODOLOGY

The approach in calculating doses arising from intrusions into tailings areas is illustrated schematically in Figure 1.1. One reference tailings site in the Elliot Lake region of northern Ontario and one reference tailings site in northern Saskatchewan were fabricated such that, to the extent feasable within the scope of this study, they would be representive of tailings management schemes in the two major uranium mining areas. The magnitudes of the radiation fields and releases to the transport media were based either on empirical data, or where data was lacking, on calculations using validated models. Doses to the intruder were then calculated based on ICRP-26 dosimetry, using dose conversion factors cited by recognized agencies, such as the International Commission on Radiological Protection or the U.S. Nuclear Regulatory Commission. The calculations were performed taking into account exposure conditions specific to each scenario. In cases of scenarios where a range of exposure

conditions appeared reasonable, the doses were calculated from the extremes of the conditions as well as from the most likely conditions.

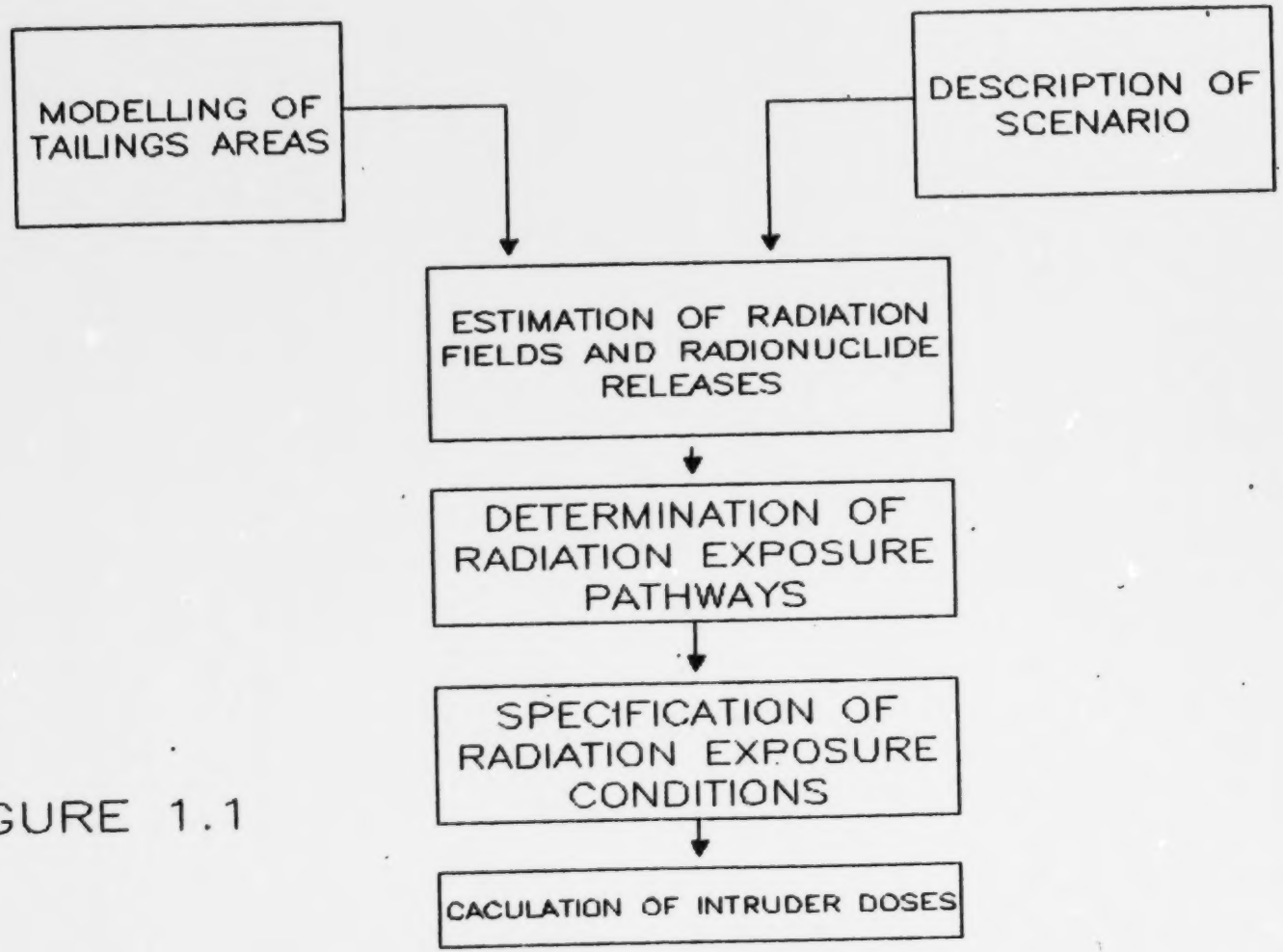
MODELLING OF TAILINGS AREAS
DESCRIPTION OF SCENARIO
ESTIMATION OF RADIATION FIELDS AND RADIONUCLIDE RELEASES
DETERMINATION OF RADIATION EXPOSURE PATHWAYS
SPECIFICATION OF RADIATION EXPOSURE CONDITIONS
CACULATION OF INTRUDER DOSES

FIGURE 1.1

METHODOLOGY FOR INTRUDER DOSE ASSESSMENT

2.0 REFERENCE TAILINGS AREAS

As discussed in Section 1.3, the study logic includes developing a reference tailings area for the Elliot Lake region of northern Ontario and a reference tailings area for northern Saskatchewan. These reference sites form the basis from which the doses to intruders are calculated for various scenarios. In addition, and if feasible, that is, if the estimated doses were not too dissimiliar between the northern Ontario and northern Saskatchewan reference sites, the characteristics of the two reference sites would be folded into a generic "site", that would be applicable for both active uranium mining regions in Canada.

2.1 OVERVIEW OF TAILINGS MANAGEMENT IN CANADA

In general there are three basic types of tailings management schemes: (Chambers,1982):
-- dry land sites;
-- land/shallow water combination sites; and
-- underwater disposal sites.

Dry land sites, such as the type normally found in the southwestern United States, are typically located in flat or gently sloping topography. These occupy large areas and require dykes or dams to contain the tailings.

The land/shallow water combinations are located in a valley, marsh or other low lying area. Usually a dam is required to create a basin for the tailings. The Elliot Lake sites, Rabbit Lake and Cluff Lake practice this type of tailings management. However, at Cluff Lake, this management scheme only applies to the tailings arising from processing the conventional grade ore.

In underwater disposal, tailings would be placed below the water surface, such as at the bottom of a lake. This type of disposal would protect the tailings from winds and surface waves, and minimize radon emissions. Underwater disposal had been practiced at the Beaverlodge site prior to the site closing.

2.2 SPECIFICATION OF REFERENCE TAILINGS AREAS IN ELLIOT LAKE AND NORTHERN SASKATCHEWAN

2.2.1 GENERAL STATEMENT

The characteristics required to model the radiation levels and releases of radioactivty from the Elliot Lake and northern Saskatchewan reference tailings sites are given in Table 2.1. Relevant meteorological parameters pertaining to both sites are listed in Table 2.2.

The characteristics of the Elliot Lake reference site were derived principly based on those of the Nordic site. It is instructive to note

that the characteristics of the Nordic site are reasonably similiar to those of the Elliot Lake Reference site (Beak,1983a) as shown in Table 2.3. Also, as the Nordic tailings has been the subject of considerable investigation, a reasonably comprehensive data base exists facilitating the calculation of meaningful radiation field intensities and releases of radioactivity.

The northern Saskatchewan reference site characteristics are drawn primarily from those of the Rabbit Lake site. The rationale for proceeding in this manner was as follows:
-- Only two of the sites, the Rabbit Lake site and the Beaverlodge site, have sufficiently developed data bases. For example, at the time of preparing this report, a decision on the final disposition of the leach tailings at Cluff Lake had not been taken, accordingly, incorporating the characteristics of the Cluff Lake site into those of the reference northern Saskatchewan tailings area was not considred to be valid at this time.
-- Notwithstanding that the underwater disposal management scheme at the Beaverlodge site precludes many of the intrusion scenarios, in the somewhat unlikely event that at some time in the future, the lakes into which the tailings are deposited were to be drained, the conditions would then tend to resemble those at the Rabbit Lake site.
-- The Key Lake site is an engineered above-ground facility and therefore, based on discussions with A.E.C.B. staff, represents a highly improbable site for the majority of the postulated intrusions.

In summary, the data currently available from the northern Saskatchewan sites at this time are very sparce and a truly generic reference site, for this mining region, could not be developed meaningfully at the time of preparation of this report. The methodology, however, employed in this study could be applied at a later date when appropriate data become available.

As the specifications of the reference sites are drawn largely from those of the Nordic and Rabbit Lake tailings areas, brief descriptions of these sites are given below.

2.2.2.1 NORDIC TAILINGS SITE

The Nordic tailings area is located approximately 5 km east of the town of Elliot Lake and received tailings from the Nordic mill operating at a nominal rate of 3000 tonnes per day. The tailings were deposited initially in a low-lying area west of the mill and subsequently, after the construction of waste embankments, the tailings were placed east, south and west of a contiguous area north of the mill. The tailings are very heavily acidic, due to the high pyrite content of the ore, influencing the rate of leaching of the radioisotopes from the tailings material. Liquid effluent from the tailings area is directed to a lime and barium treatment plant for neutralization and radium precipitation. A more complete description is available from MacLaren (1977) and Moffett (1977).

Based on the data from Dave (1984), a histogram was constructed of the radium-226 concentration at different depths from the tailings surface. Figure 2.1 shows that the concentration does not vary by more

than 35% over the top 40.cm. Data for the Stanrock tailings (Bigu,1984), although demonstrating more variability than the Nordic tailings (Figure 2.2), also indicate that concentration of radium-226 with depth into the tailings material is reasonably uniform. The particle size distribution of uranium tailings core samples (Murray,1981), as presented in Figure 2.3, tends to indicate that only about 30% of the particles may be respirable, i.e. particles having diameters less than 20 um. The assignment of the respirable fraction is based on the assumption that the size distribution of the airborne particulates is similiar to that of the core samples; an assumption that requires empirical verification.

2.2.2 RABBIT LAKE TAILINGS SITE

The Rabbit Lake tailings area receives the waste material from the acid leach mill. The tailings are rendered alkaline (pH~8) prior to release. The small amount of pyrite in the ore is destroyed by the milling process and consequently sulfide is not detected in the tailings (Larson,1982). The tailings are discharged into an impoundment located above the water table. Decant from the tailings is treated with barium chloride and added flocculant.

The radiological information on the Rabbit Lake tailings is sparce. Notwithstanding the large data base on uranium tailings maintained by CANMET, no information on measured values of radionuclide concentration in the tailings material is available (John, 1985). Accordingly, the radiological data contained in this report are based on the theoretical estimates prepared by MacLaren (1984). Eldorado Resources are planning a detailed radiological assessment of the Rabbit Lake tailings with an estimated completion date of 1987 (Filion,1985). When the results of the study become available, the doses to intruders could be recalculated based on the site specific data, utilizing the methodology of this study.

TABLE 2.1

REFERENCE TAILINGS AREAS MODELLING PARAMETERS

PARAMETERS	ELLIOT LAKE	NORTHERN SASKATCHEWAN
AREA (ha)	110	50
AVERAGE DEPTH (m)	4 - 7	8.5
WATER TABLE DEPTH	10 - 12	12.5
MASS (MT)	12	5.9
POROSITY	0.4 - 0.6 (a)	0.7
DENSITY (g/cm^{-3})	1.5 - 1.7 (a)	1.5
MOISTURE CONTENT %	6.5 - 37.6 (a)	77 - 109
DRY SURFACE %	87	40
PYRITE CONTENT %	4 (at 1 m)	negligible

RADIOLOGICAL PROPERITIES

Radionuclide Concentrations in Tailings Material (Bq/g)		
U-238-234	0.20	7
Th-230	1.2	38
Ra-226	6.7	38
Pb-210	8.1	38
Po-210	8.1 (b)	38
Th-232	1.8	0.38 (d)
Th-228	5.2	0.38 (d)
Ra-228	1.8 (c)	0.38 (d)

FOOTNOTES TO TABLE 2.1

1.Elliot Lake reference tailings site characteristics derived from those of Nordic tailings area except as noted. Data from MacLaren (1977) with the following exceptions:
i) Depth of Tailings from Moffet (1977)
ii) Water table depth from Moffett (1977)
iii) % Dry Surface from MacLaren (1978)
iv) Radiological Properties from Dave (1984) and Moffett (1977)
2. Northern Saskatchewan reference tailing site characteristics derived from those of Rabbit Lake tailings area. Data from MacLaren (1984) and Filion (1985).
3. Stanrock parameters from Bigu (1984).

(a) Stanrock tailings area parameter assumed appliicable.
(b) Assumed to be in secular equilibrium with Pb-210
(c) Asssumed to be in secular equilibrium with Th-232. Measured average concentration for Th-228 from Dave 1984 should be confirmed.
(d) Assumed to be 1% of the activity of the U-238 series radioisotopes.

TABLE 2.2

METEOROLOGICAL PARAMETERS

	ELLIOT LAKE	NORTHERN SASKATCHEWAN
Mean Annual Temperature °C	4	-2
Mean Annual Frost Free Period (days)	129	146
Mean Annual Precipitation (mm)	752	360 - 560
Snowfall Equivalent (mm)	209	137 - 244
Evaporation Values (cm)	56	50 - 60
Duration of Snow Cover (months)	4.5	7.2
Stable Condition of Atmosphere (%)	22	25

From MacLaren (1977), and Beak (1980)

TABLE 2.3

COMPARISON OF MODELLING PARAMETERS OF THE ELLIOT LAKE REFERENCE SITE IN THIS STUDY AND THOSE OF THE ELLIOT LAKE SITE DEVELOPED IN THE BEAK STUDY(1983A)

PARAMETERS	ELLIOT LAKE	BEAK REFERENCE
AREA (ha)	110	40
AVERAGE DEPTH (m)	4 - 7	10
WATER TABLE DEPTH	10 - 12	11-12.5
MASS (MT)	12	4.2
POROSITY	0.4 - 0.6	0.4
DENSITY (g/cm^{-3})	1.5 - 1.7	1.6
MOISTURE CONTENT %	6.5 - 37.6	N.S.
DRY SURFACE %	87	N.S.
PYRITE CONTENT %	4 (at 1 m)	1

RADIOLOGICAL PROPERITIES

	Radionuclide Concentrations in Tailings Material (Bq/g)	
U-238-234	0.20	0.93
Th-230	1.2	1.5
Ra-226	6.7	12.4
Pb-210	8.1	13
Po-210	8.1	13
Th-232	1.8	1.5
Th-228	5.2	1.5
Ra-228	1.8	1.5

N.S. -- not stated

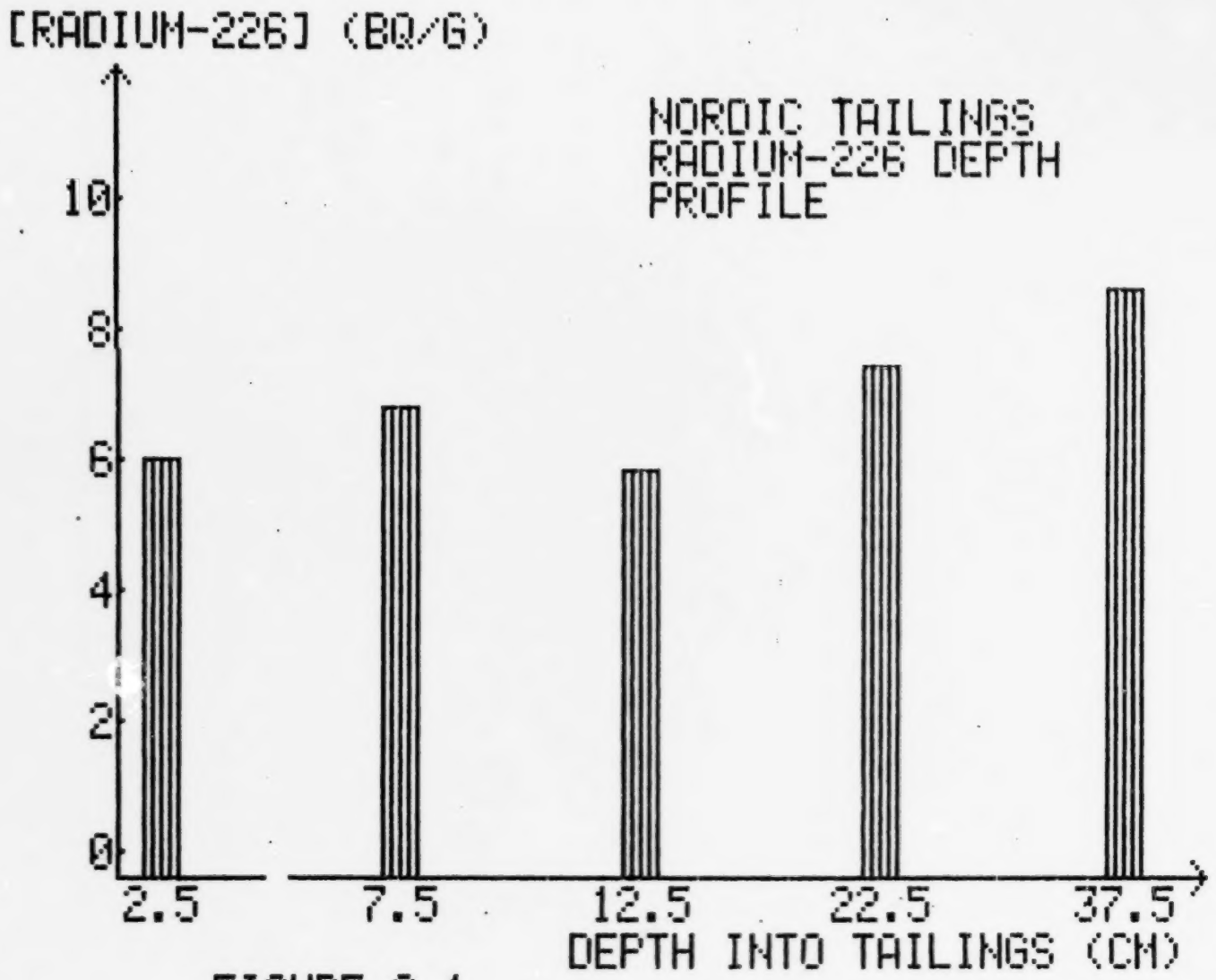
[RADIUM-226] (BQ/G)
NORDIC TAILINGS
RADIUM-226 DEPTH
PROFILE
10
8
6
4
2
0
2.5
7.5
12.5
22.5
37.5
DEPTH INTO TAILINGS (CM)

FIGURE 2.1

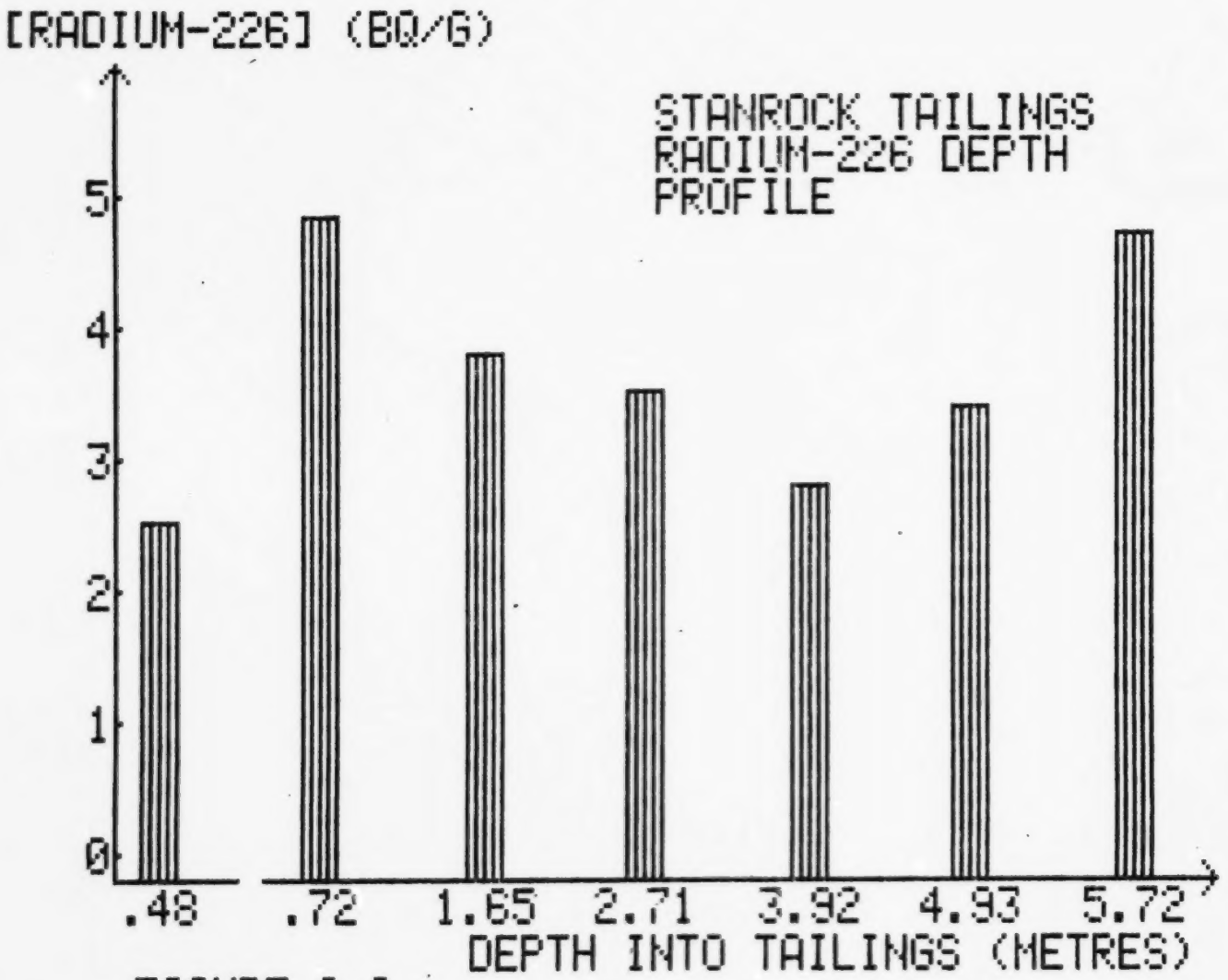
[RADIUM-226] (BQ/G)
STANROCK TAILINGS
RADIUM-226 DEPTH
PROFILE
5
4
3
2
1
0
.48
.72
1.65
2.71
3.92
4.93
5.72
DEPTH INTO TAILINGS (METRES)

FIGURE 2.2

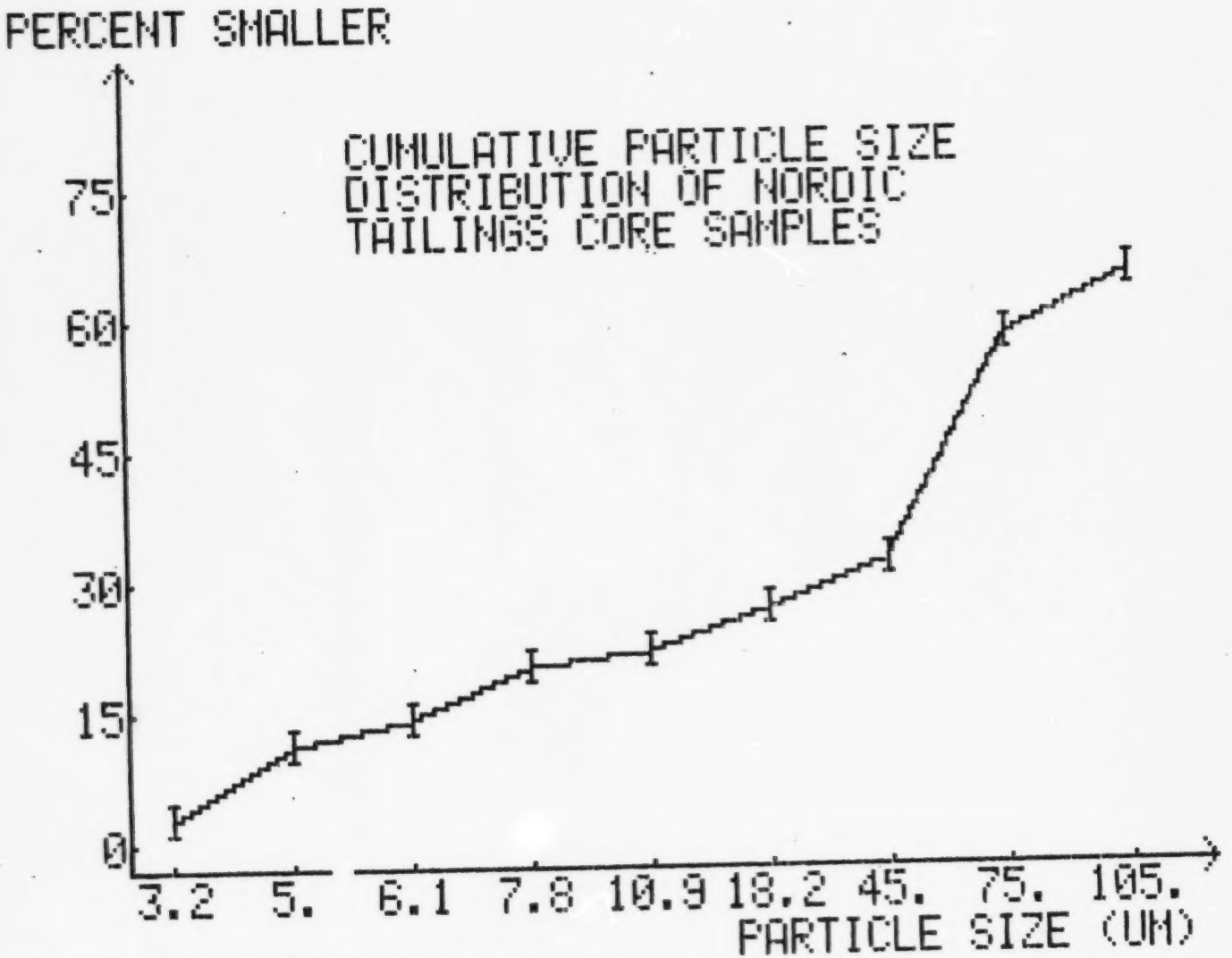
PERCENT SMALLER
CUMULATIVE PARTICLE SIZE
DISTRIBUTION OF NORDIC
TAILINGS CORE SAMPLES
75
60
45
30
15
0
3.2
5.
6.1
7.8
10.9
18.2
45.
75.
105.
PARTICLE SIZE (UM)

FIGURE 2.3

3.0 RADIATION DOSIMETRY AND PATHWAY ANALYSIS

3.1 RADIATION DOSIMETRY

Dosimetry calculations are based on ICRP-26 (1977). The effective dose equivalent He is defined as:

$$He = \sum Wt\ Ht \qquad \text{(Eq. 3.1)}$$

where:

Ht is the dose equivalent to tissue t
Wt is the weighting factor for each tissue.

The values of the weighting factors are given in ICRP-26.

3.1.1 EXTERNAL DOSIMETRY

Whole body doses arising from exposure to external gamma radiation are calculated in terms of effective dose equivalent, whilst skin doses are given in terms of effective dose to tissue at a depth of 70 um. For exposure to ground contamination, the external dose conversion factor, EDCF= 0.8 (CEC,1979), converts the dose in air at 1 m to effective dose equivalent. This value was used in this study as it was developed by a consensus agency, the Commission of Europeon Communities, and furthermore it is consistent with the conversion factor of 0.87 Sv/Gy recently cited by Hunt, (1984).

Water immersion dose conversion factors for effective dose equivalent and dose to the skin from gamma and beta radiations at an effective depth of 7 mg/cm^2 are derived from the values cited in Beak (1983a) which, in turn, are based on the water immersion dose conversion factors calculated by Kocher (1979) and Kocher and Eckerman (1981). The values are given in Table 3.1.

3.1.2 INTERNAL DOSIMETRY

Doses resulting from the intake of radioactive materials are expressed in terms of committed effective dose equivalent for whole body doses and committed dose equivalents for doses to various tissues. The dose conversion factors for organ committed dose equivalents and committed effective dose equivalent per unit intake for the adult were taken from the U.S. Nuclear Regulatory Commission report NUREG/CR-3332 (1983). It is instructive to note that the effective dose equivalent conversion factors in NUREG/CR-3332 and those in Beak (1983b) are consistent to within a few percent. As the values in NUREG/CR-3332 respresent the position of a recognized agency, it was decided to use these values for this study. The factors corresponding to intakes of radioactivity through inhalation are given in Table 3.2, while those for ingestion in Table 3.3. For exposures resulting from the inhalation of uranium, dose conversion factors are given for lung clearance classes Y and W. Similiarly, for exposures resulting from the ingestion of uranium, dose conversion factors are provided for

both soluble and insoluble compounds. This approach was adopted as Kalkwarf (1979) reported that both W and Y class airborne uranium particulates were identified in both uranium ores and in tailings piles materials.

Dose equivalent conversion factors have been developed for exposure to radon daughters. Wicke (1984) cited a factor of 0.061 mSv/Bq m^{-3} while Lindell (1984) uses a conversion factor of 0.1 mSv/Bq m^{-3} or 370 mSv/WL. Lindell's value is consistent with ICRP-39 (1984) and will be used in this study.

3.2 PATHWAY ANALYSIS

The doses to the intruder into a uranium tailings area are calculated based on the concepts developed by Leddicotte (1978) and complemented by the methodology described in MacLaren (1982). Empirical data from uranium and non-uranium tailings areas are utilized, wherever possible, to specify the pathway parameters.

Figure 3.1 illustrates the major exposure pathways whereby an intruder into a uranium tailings area will receive radiation exposure. These are summarized as follows:

- Inhalation of radioactive particulates,

- Inhalation of radon daughters,

- Ingestion of dissolved radionuclides in water,

- Ingestion of food (vegetables and meat) produced in contaminated soil,

- Direct exposure from gamma radiation from the contaminated soil,

- Direct exposure from gamma and beta radiation from submersion in contaminated water.

The methodology used in this study to calculate the doses resulting from the significant exposure pathways is discussed in the following sections.

3.2.1 INHALATION OF RADIOACTIVE PARTICULATES

The annual dose from the inhalation of particulate radioactivity is given by:

$$Dn = K\ R\ Ua\ Tx\ Cn\ DECFn \quad \text{---------- (Eq. 3.2)}$$

where:

K

Dust loadings.

Information about fugitive dust releases from tailings areas is

very sparse. Data in MacLaren (1978) show that there are large day-to-day variations in the dust loadings near the Nordic tailings with the majority of readings below 50 ug/m^3, a few values above 1000 ug/m^3 and similarly a few values below 20 ug/m^3. Although many sources were approached for data, there is no evidence that dust loadings at the Rabbit Lake site had been measured at the time of preparation of this report.

Data on dust levels during construction activities do not appear to be available from the Ontario Ministry of Transport or Transport Canada. The U.S. Environmental Protection Agency (1977) has published some guidance on dust loading during road construction, however, the applicability of this information to the tailings situation is unclear as the environmental conditions differ significantly. In the study on the development of an assessment methodology for near surface waste disposal, MacLaren (1982) cited dust loadings of 565 ug/m^3 during high mechanical activity and 50 ug/m^3 during low mechanical activity periods. In their evalution of decommissioning alternatives of Rabbit Lake Tailings Area, MacLaren (1984) used the following dust loadings values:

Source	Total Particulates (ug/m^3)
Construction	30
Trucking	50
Wind Blown	10

The lower dust loading, attributed to the Rabbit Lake site, as compared to the Nordic site is consistent with the much higher moisture content of the Rabbit Lake tailings.

From the above, the dust loadings under different conditions are taken to be:

	Elliot Lake (ug/m^3)	Northern Saskatchewan (ug/m^3)
High Activity	1000	50
Low Activity	50	10
Wind Blown	30	10

It is recognized that the basis for assigning the above dust loading values is contentious, and that more comprehensive empirical data are needed to accurately evaluate dust loadings and hence airborne radioactive particulate concentrations on tailings areas.

Ua

Breathing rates.
2.6 m^3/h during heavy work; (ICRP-23,1975)
0.96 m^3/h during normal activity; (ICRP-23,1975)
0.8 m^3/h during indoor activity; (Wicke,1984)

R

Respirable fraction.
For the base case, the total activity is considered respirable. However, from Figure 2.3, it might be postulated that less than 30% of the airborne activity is of this class. This is consistent with dust measurements at Elliot Lake taken by the Mines Branch of the Department of Energy Mines and Resources (MacLaren,1977). In this survey, the respirable dust concentrations ranged from 8.2 to 10.7 mg/m^3 whilst the total particulate was measured at 32 mg/m^3, accordingly suggesting a respirable fraction of approximately 30%.

Tx

Duration of each exposure condition; (hours/year).

Cn

Specific Activity of radionuclide in tailings materials; (Table 2.1).

DECFn

Effective dose equivalent and organ dose equivalent Conversion Factors for radionuclide n; (Table 3.2).

3.2.2 INHALATION OF RADON DAUGHTERS

Prediction of the concentration, in houses, of radon daughters arising from the decay of radium in soil is difficult due to the complex nature of the situation. In fact, an attempt to establish a methodology to identify dwellings in which the radon levels may be above consensus guidelines was the subject of a recent paper (Eaton, 1984), the salient points of which are described below.

Assuming the building materials contain normal background levels of radioactivity, elevated radon concentrations in houses located on uranium tailings areas are caused by the entry of gas containing radon generated in the soil. The rate at which soil gas enters the room depends on (DSMA, 1983):

- pressure differential between house and soil,
- resistance of the foundations to gas flow,
- resistance of the soil itself to gas movement.

The radon concentration in a building depends on (DSMA, 1983):

- radon supply (soil gas flow x radon concentration),
- building volume,
- ventilation rate.

The equilibrium factor F between the concentration of the radon daughters and the concentration of radon has been investigated thoroughly and found to depend on the particular characteristics of the house and the living habits of the occupants. However, the ventilation rate is the most important factor. Swedjemark (1983) cites the following values for F based on ventilation rates which are compared to those derived from data in UNSCEAR (1982):

	Average Equilibrium Factor, F	
	Swedjemark	UNSCEAR
Air Exchange Rate		
Low - 1 < 0.3/h	0.51	0.85
Average - 0.3 < 1 < 0.6/h	0.43	0.65
High - 1 > 0.6/h	0.33	0.5

Both sets of equilibrium factors will be utilized in this study to calculate radon daughter concentrations.

The doses resulting from exposures to radon daughters for scenarios, in which the exposures are received outdoors, appear negligible under most meteorological conditions, perhaps with the exception of Pasquill Types F and G weather. These low levels of radon daughters are exemplified by the findings of MacLaren (1978) where the radon daughter measurements at tailings areas in the Elliot Lake area were in the range from 0.0004 WL to 0.0009 WL. Similiarly negligible radon daughter levels were measured in an Australian open pit mine (Leach,1982), where the average radon daughter level appeared to be approximately 0.02 WL, however, the grade of the ore averaged 2%. Prorating the radon daughter levels by the ratio of the typical ore grades in Elliot Lake compared to the ore grade in the Australian mine, suggests that the airborne concentrations at the Elliot Lake tailings would be of the order of 0.002 WL. These levels are reasonably consistent with the data reported in the MacLaren study. Accordingly, radon daughter levels on the tailings, outside of structures, may be taken as being negligible.

3.2.3 INGESTION OF CONTAMINATED WATER AND FOOD

3.2.3.1 INGESTION OF CONTAMINATED WATER

The annual dose, Dnt, to tissue, t, and the annual effective dose equivalent from consumption of water containing radionuclide, n, is given by:

$$Dnt = Fw\ Iw\ Cnw\ DECFnt \quad \text{(Eq. 3.3)}$$

where:

Fw is the fraction of annual intake of water from a contaminated source.
Iw is the annual intake of water; 730 L/y Beak 1983)
Cnw is the concentration of radionuclide n in the water (Bq/L)
DECFnt is the dose conversion factor for radionuclide n (Sv/Bq).

3.2.3.2 INGESTION OF CONTAMINATED VEGETABLES

The annual dose, Dnt, to tissue, t, and the effective dose equivalent arising from the consumption of vegetables grown on contaminated soils is given by:

Dnt= Fv Iv Svn Ctn DECFnt ---------- (Eq. 3.4)

where:

Fv is the fraction of annual consumption of vegetables that are grown on the tailings.

Iv is the annual consumption of vegetables; 30 Kg/y (Tracy, 1983).

Ctn is the concentration of radionuclide n in the tailings soil.

Svn is the transfer factor for radionuclide n from soil to vegetation, (Bq/kg vegetation/Bq/kg soil).
The transfer of radionuclides from soil to leafy vegetables differs depending on the type of plant and the part of the plant considered (Tracy,1983; Kalin,1985). As the base case, transfer parameters were taken from Beak (1983b) and are presented in Table 3.4. Kalin (1985) has recently performed measurements on the uptake of radionuclides by plants grown directly on tailings soil. Although the data that were available at the time of the study, summarized in Table 3.5, demonstrate significant variability, this information suggests that the transfer of radionuclides from tailings soil to vegetation may be much greater than previously reported. Acordingly, when the complete set of data, including the transfer factors for thorium and polonium, becomes available, the impact on the dose arising from food ingestion should be evaluated.

3.2.3.3 INGESTION OF CONTAMINATED MEAT

The annual dose, Dnt, to tissue, t, or the effective dose equivalent arising from the consumption of meat contaminated with radionuclides due to the animal grazing on the tailings is given by:

Dnt= Fm Im If Svn Sgn A DECFnt ---------- (Eq. 3.5)

where:

Fm is the fraction of meat diet that is obtained from animals grazing on tailings.

Im is the annual consumption of meat; 80 kg/y (Beak, 1983b).

If is the fraction of the annual feed requirements satisfied by pasture vegetation; this is assumed to be 0.5 (Beak,1983b).

A is the feed ingestion rate; 50 Kg/d (Beak,1983b).

Sgn - transfer factor from feed to meat (d/kg). These are given in

Table 3.6: (Beak,1983b).

3.2.4 EXTERNAL RADIATION EXPOSURE

3.2.4.1 DIRECT GAMMA EXPOSURE FROM DRY TAILINGS

The gamma exposure rate X at 1 m above the surface of solid tailings is:

X = Gamma Exposure Rate (uR/h) = 2.5 C ---------- (Eq. 3.6)

Where:
C is the concentration in pCi/g of Ra-226 in the tailings (Schaiger, 1974). Analysis of the relationship between gamma dose rate and soil radium levels in the Florida phosphate mining regions (Roessler, 1978) yields a similiar relationship with the coefficient being 2.7, well within the limits of experimental errors. However, assuming a uniform distribution with depth of the radionuclides in the tailings material, which is consistent with the data presented in Figures 2.1 and 2.2, recent information developed at Oak Ridge (Kocker, 1985), would predict a coefficient of slightly over 1. In this study, pending the availability of good empirical gamma dose rate data, it was decided to continue to use the Schaiger expression to facilitate comparisons with other studies. If, as a result of future studies, newly acquired empirical data suggest a different coefficient, the dose results reported in this study could readily be scaled.

The effective dose equivalent from direct exposure to gamma rays from radionuclides in the tailings material is given by:

$DE_x = X\ S\ EDCF\ T_x\ 10^{-6}$ ---------- (Eq. 3.7)
where:

X
Exposure rate in uR/h

S
Shielding Factors

Structure or Location	Shielding Factor *
1 m above infinite smooth surface (Assumed to apply to undisturbed tailings)	1.0
1 m above ordinary ground (Assumed to apply to tailings that have become uneven due to either construction or agricultural activities.)	0.7
One and two story frame houses	0.4

* From WASH-1400 (USNRC,1975)

Cars on Roadways 0.5
(This factor is similiar to the value of 0.4 reported by Lauridsen (1983).

EDCF
External Dose Conversion Factor; 0.8. (See section 3.1.1)

Tx
Annual duration of exposure. (Hours/year)

10^{-6}
Factor to convert uR to Gy.

3.2.4.2 BETA-GAMMA EXPOSURES FROM IMMERSION IN CONTAMINATED WATER

DEn = Cn Tx EDCFn ---------- (Eq. 3.8)

where:

DEn
Effective dose equivalent arising from exposure to radionuclide n.

Cn
Concentration of radionuclide n.

EDCFn
Effective dose equivalent conversion factor for radionuclide n: Table 3.1.

An expression analogous to Equation 3.8 is used to calculate the doses to the skin (tissues at depths of 70 um).

TABLE 3.1

DOSE CONVERSION FACTORS for EFFECTIVE DOSE EQUIVALENT AND SKIN DOSE(mSv/hr per Bq/Litre) for IMMERSION in CONTAMINATED WATER

NUCLIDE	PCI/L	BQ/L	EDE	SKIN
U-238	27	1	.0000999	.002349
U-234	27	1	6.21E-6	7.56E-6
TH-230	27	1	5.94E-6	7.29E-6
RA-226	27	1	.00702	.0108
PB-210	27	1	1.863E-5	.000783
PO-210	27	1	3.51E-8	4.32E-8
TOTAL U			.0071507	.0139469
TH-232	27	1	4.86E-6	6.21E-6
RA-228	27	1	.00378	.00567
TH-228	27	1	.00621	.00999
TOTAL TH			.0099949	.0156662
TOTAL			.0171456	.0296131

TABLE 3.2

COMMITTED DOSE EQUIVALENT PER UNIT INTAKE
VIA INHALATION (Sv/Bq)

NUCLIDE	ACT(PCI)	ACT (BQ)	GONADS	BREAST	R MARROW	LUNGS	THYROID	ENDOSTEAL	REMAIND	EFF DE
U-238-Y	27	1	2.42E-9	2.91E-9	6.88E-8	.000266	2.73E-9	1.01E-6	9.61E-8	.000032
U-238-W	27	1	6.71E-9	6.74E-9	1.98E-7	.0000142	6.71E-9	2.94E-6	2.54E-7	.0000019
U-234-Y	27	1	2.65E-9	2.68E-9	7.22E-8	.000298	2.65E-9	1.13E-6	1.08E-7	.0000358
U-234-W	27	1	7.52E-9	7.52E-9	2.1E-7	.000016	7.52E-9	3.29E-6	2.85E-7	2.13E-6
TH-230	27	1	1.72E-7	1.72E-7	.0000699	.000301	1.72E-7	.000871	4.48E-7	.0000707
RA-226	27	1	1.02E-7	1.02E-7	6.64E-7	.0000161	1.02E-7	7.59E-6	1.07E-7	2.32E-6
PB-210	27	1	3.18E-7	3.18E-7	3.75E-6	3.18E-7	3.18E-7	.0000547	4.69E-6	3.67E-6
PO-210	27	1	4.04E-7	4.04E-7	4.04E-7	7.29E-7	4.04E-7	4.04E-7	.0000074	2.54E-6
TOT U			1.015E-6	1.016E-6	7.527E-5	9.123E-4	1.016E-6	9.421E-4	1.339E-5	1.511E-4
TH-232	27	1	5.98E-7	6.14E-7	.000401	.00094	5.99E-7	.00499	1.51E-6	.000311
TH-228	27	1	2.26E-7	2.32E-7	.0000187	.000691	2.3E-7	.000229	6.05E-7	.0000923
RA-228	27	1	1.83E-7	1.84E-7	7.38E-7	7.22E-6	1.93E-7	6.51E-6	1.97E-7	1.29E-6
TOT TH			1.007E-6	1.03E-6	4.204E-4	.0016382	1.012E-6	.0052255	2.302E-6	4.046E-4
TOTAL			2.022E-6	2.046E-6	4.957E-4	.0025506	2.028E-6	.0061676	1.569E-5	5.557E-4

TABLE 3.3

COMMITTED DOSE EQUIVALENT PER UNIT INTAKE
VIA INGESTION (Sv/Bq)

NUCLIDE	ACT(PCI)	ACT (BQ)	GONADS	BREAST	R MARROW	LUNGS	THYROID	ENDOSTEAL	REMAIND	EFF DE
U-238-I	27	1	1.02E-10	9.33E-11	2.72E-9	9.22E-11	9.2E-11	4.04E-8	1.61E-8	6.42E-9
U-238-S	27	1	2.31E-9	2.31E-9	6.8E-8	2.3E-9	2.3E-9	1.01E-6	9.69E-8	6.88E-8
U-234-I	27	1	1.06E-10	1.03E-10	2.88E-9	1.03E-10	1.03E-10	4.52E-8	1.77E-8	7.06E-9
U-234-S	27	1	2.59E-9	2.58E-9	7.21E-8	2.58E-9	2.58E-9	1.13E-6	1.09E-7	7.66E-8
TH-230	27	1	6.82E-10	6.8E-10	2.89E-7	6.8E-10	6.8E-10	.0000035	1.54E-8	1.48E-7
RA-226	27	1	9.16E-8	9.17E-8	5.98E-7	9.16E-8	9.15E-8	6.83E-6	1.03E-7	3.58E-7
PB-210	27	1	1.25E-7	1.25E-7	1.48E-6	1.25E-7	1.25E-7	.0000216	1.85E-6	1.45E-6
PO-210	27	1	8.23E-8	8.23E-8	8.23E-8	8.23E-8	8.23E-8	8.23E-8	1.52E-6	5.14E-7
	0									
TOT U			3.047E-7	3.048E-7	2.595E-6	3.047E-7	3.046E-7	3.424E-5	3.728E-6	2.629E-6
TH-232	27	1	1.25E-9	1.26E-9	1.48E-6	1.25E-9	1.21E-9	.0000185	1.47E-8	7.38E-7
TH-228	27	1	2.53E-9	2.33E-9	1.93E-7	2.31E-9	2.3E-9	2.37E-6	3.86E-8	1.07E-7
RA-228	27	1	1.58E-7	1.57E-7	6.53E-7	1.57E-7	1.57E-7	5.82E-6	1.63E-7	3.88E-7
TOT TH			1.618E-7	1.606E-7	2.326E-6	1.606E-7	1.605E-7	2.669E-5	2.163E-7	1.233E-6
TOTAL			4.665E-7	4.654E-7	4.921E-6	4.652E-7	4.651E-7	6.093E-5	3.944E-6	3.862E-6

TABLE 3.4

TRANSFER PARAMETERS FROM SOIL TO PLANT

NUCLIDE	ABOVE GROUND VEGETATION	BELOW GROUND VEGETATION	PASTURE GRASS
U	2.5E-3	2.5E-3	2.5E-3
Th	4.2E-3	4.2E-3	4.2E-3
Ra	1.4E-2	3.0E-3	1.8E-2
Pb	4.0E-3	4.0E-3	2.8E-2
Po	1.0E-3	1.0E-3	1.0E-3

From Beak (1983b)

TABLE 3.5

TRANSFER OF RADIONUCLIDES FROM SOIL TO PLANT

TYPE/PART	RADIUM-226	LEAD-210	URANIUM
PUCCINELLIA DISTANS			
roots/tailings	0.3	0.23	3.84
leaves & stems/roots	0.09	0.15	0.39
fruit/leaves & stems	0.71	0.15	0.39
POPULUS TREMULOIDES			
roots/tailings soil	0.23	0.62	0.19
stem/roots	0.77	0.41	0.062
leaves/stems	0.94	0.71	2.33
SCREPES SCREPERNIS			
roots/tailings soil	0.23	2.1	0.22
stem/roots	0.36	0.08	0.12
leaves/stem	1.46	0.96	0.46
fruit/stem	1.17	0.46	0.14
fruit/leaves	0.8	0.48	0.31
HORDEUM JUBATUM			
roots/tailings soil	0.38	0.26	2.94
leaves & stem/roots	0.16	0.16	0.38
fruit/stem & leaves	0.34	0.55	0.086

From Kalin (1985)

TABLE 3.6

TRANSFER PARAMETERS FROM FEED TO MEAT (DAY/KG)

NUCLIDE	BEEF
U	3.4E-4
Th	2.0E-4
Ra	5.1E-4
Pb	7.1E-4
Po	1.2E-2

From Beak (1983b)

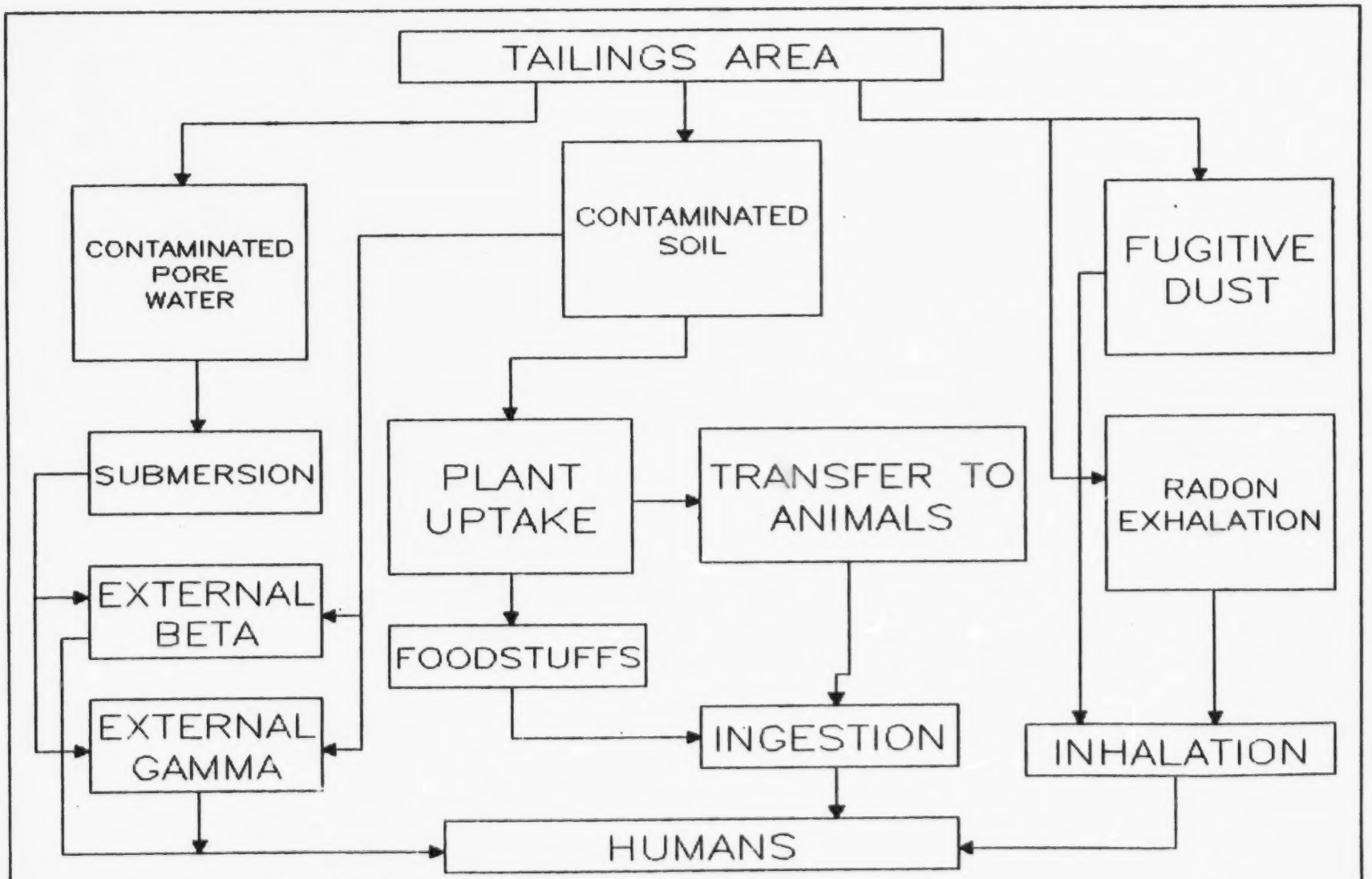

FIGURE 3.1

MAJOR INTRUDER PATHWAYS FOR INTRUDER SCENARIOS

4.0 DOSE ESTIMATES

4.1 INTRUDER-HABITATION SCENARIO

4.1.1 HUT

DESCRIPTION:

Because of the nature of the tailings areas, living in a structure of any size which is located on these sites is unlikely. However, it is conceivable that a primitive structure, such as a hut, would be constructed as a squatters residence. (Such an occurrence is reported, by local residents, to have taken place on the Kirkland Lake gold mining tailings, where an elderly person known as the "Tails Lady" is said to be living in a shack situated directly on the tailings.) In this scenario, the dwelling is assumed to be a one story wooden structure with no foundation, and the floors constructed from 2.54 cm (1") boards. The ventilation rate is assumed to be several air changes per hour and heating is provided by a wood burning stove.

EXPOSURE PATHWAYS:

The significant exposure pathways are:

- Direct gamma exposure from tailings.
- Internal radiation exposure arising from the inhalation of particulate radioactivity.
- Internal radiation exposure arising from the inhalation of radon daughters.

ASSUMED EXPOSURE CONDITIONS:

Occupancy factor of dwelling - 0.8 (UNSCEAR, 1982).

RADIATION FIELDS AND RADIOACTIVITY CONCENTRATIONS:

	Elliot Lake	Northern Saskatchewan
Gamma Dose Rates:		
Standing position (uGy/h)	4.1	23
(Shielding factor = 0.9)		
Airborne Particulates Concentrations		
Dust Loading (ug/m^3)	30	10

Radionuclide concentrations:	$m3q/m^3$	mBq/m^3
U-238-234	0.006	0.070
Th-230	0.035	0.38
Ra-226	0.20	0.38
Pb-210	0.24	0.38
Po-210	0.24	0.38
Th-232	0.054	0.0038
Th-228	0.16	0.0038
Ra-228	0.054	0.0038

Prediction of the radon daughter levels is difficult. Bigu (1984) reported on radon daughter levels, which range from 0.27 to 2.7 WL, measured in a rudimentary hut constructed on the Stanrock tailings area. Dave (Personal communication, 1985) indicated that 1.5 WL would represent a reasonable average of these measurements. The radium concentration of the tailings material at the location of the hut was also measured and found to be 3.4 Bq/g. Bigu (1984), as part of the same study, reported the range of the radon gas concentrations in tailings soil to be 52 to 74 Bq/L. In addition, the radon flux at the surface was determined to average approximately 13 Bq/m^2-s, the range being 0.6 - 28 Bq/m^2-s (Bigu, 1984). It is recognized that the reported radon flux is unexpectedly high as the Schaiger (1974) relationship between the radon flux and radium content of an infinitely thick tailings (J=1.6 (radium)) would predict a flux of approximately half the above value.

Measurements at the Nordic site (MacLaren,1978) indicate that the range of values of the surface radon flux range lies between 4.4 Bq/m^2-s to 14.4 Bq/m^2-s with the mean being 8.7 Bq/m^2-s. Although measurement results at the higher end of the range are more consistent with the value predicted by the Schaiger relationship, the mean value of the flux, 8.7 Bq/m^2-s, is used as the base case for calculating the radon daughter concentrations in the model huts on the tailings. In addition,the doses based on the extreme values of the empirically determined radon fluxes are also calculated.

From the above, it is expected that the radon daughter levels in a hypothetical hut on the Elliot Lake reference tailings site will be approximately 1.0 WL, with a probable range of 0.5 to 1.7 WL. For the Saskatchewan reference site, the radon daughter levels in a hut are assumed to be approximately 0.47 WL which is calculated from the ratio of the radon emanation rates of the Rabbit Lake site to that of the Nordic site. In the absence of site specific data, the percentage variability of the levels in a hut on the Saskatchewan reference tailings is considered to be similiar to that of the Elliot Lake site.

INTRUDER DOSE ESTIMATES:

The committed effective dose equivalent and the committed organ doses arising from the inhalation of radioactive particulates are given in Tables 4.1 and 4.2 for the Nordic and Rabbit Lake sites respectively.

The doses are summarized below:

Effective Dose Equivalent (mSv)

	Elliot Lake	Northern Saskatchewan
Direct Gamma Radiation	20	120
Inhaled Particulates	0.2	0.2
Inhaled Radon Daughters	360 (180 - 610) *	170 (90 - 300) *

* Range of potential doses.

The above represents the best estimates of the exposures to an intruder living in a hut on the tailings. However, given the uncertainties in the calculations, the potential range of the doses incurred from the inhalation of radon daughters, the most significant contributor to the exposures, were calculated and are given in parentheses.

4.1.2 HOUSE

DESCRIPTION:

Although considered highly improbable, the doses resulting from the scenario of the construction of a more permanent dwelling on the tailings are estimated to provide data in the event that such a scenario becomes more likely, some time in the future. For modelling purposes, the house is assumed to be a one floor house of standard design with an average air ventilation rate of 1 air change/hour.

EXPOSURE PATHWAYS:

The major exposure pathways are the same as those considered for the hut scenario:
-- external gamma exposure, and,
-- internal exposures from inhalation of radioactive particulates and radon daughters.

RADON DAUGHTER LEVELS:

Using the methodology of Goldsmith (1978), the resultant average radon concentration can be calculated from the following expression:

$$C = J.A/((\lambda v+\lambda r).A.H)$$

where:

J = Radon Flux (Bq/m^2-s)
C = Radon concentration in the house (Bq/m^3)
A = House surface area (m^2)
λv = Ventilation rate (s^{-1})
λr = Radiation decay constant (s^{-1})
H = Average house height (3m)

Accordingly, for a radon flux of 8.7 Bq/m^2-s, the radon concentration would be approximately 13 Bq/L. Based on an F factor of

0.33, the radon daughter concentration in the house will approximate 1 WL. This value appears consistent with the radon daughter concentrations measured in two buildings constructed on contaminated soil in Salt Lake City (Haywood, 1977), in which the average level was 0.94 WL. In Sweden where houses were built on abandoned waste sites containing tailings from alum shale mining, it was found that the average radon daughter concentration was 0.14 WL. The radium-226 concentration of the shale waste was approxiamately 1.3 Bq/g (Swedjemark, 1981). Based on this information, similiar houses located on the Elliot Lake Reference tailings area would exhibit indoor radon daughter concentrations of approximately 0.72 WL; a value not very dissimiliar to the value of 1 WL obtained from the Goldsmith expression.

Variations of the scenario could involve constructing more energy efficient structures by reducing the ventilation rates. Equilibrium factors as cited by Swedjemark and by UNSCEAR (Section 3.2.2) are used to determine the radon daughter levels in order to demonstrate the potential variability of the estimated exposures. The radon daughter concentrations and the corresponding doses are given below for the Elliot Lake reference site.

	Swedjemark		UNSCEAR	
Air Exchange Rates	Radon Daughter Concentration	Dose Equivalent	Radon Daughter Concentration	Dose Equivalent
(h^{-1})	(WL)	(Sv)	(WL)	(Sv)
1	0.97	0.36	1.5	0.53
0.5	2.5	0.93	3.8	1.4
0.25	6.0	2.2	10.0	3.7

GAMMA RADIATION FIELDS:

The gamma dose rates will be lower, of the order of 40%, in the dwelling, than in the hut due to the increased shielding provided by the foundation and walls of the house.

INHALED PARTICULATES:

No credit, due to the presence of a building, should be taken for reduction of exposure to radioactive particulates (USNRC, 1975). Also as the contribution to the total dose from this pathway is a very small component of the total dose, it may be assumed that the doses to the inhabitants of a house, from inhaled particulates, will be the same as the doses to the occupants of the hut.

INTRUDER DOSE ESTIMATES:

The estimated annual doses received by the intruder living in a house located directly on the tailings are summarized below:

	Effective dose equivalent	
	Elliot Lake	Northern Saskatchewan
	mSv	mSv
Direct Gamma Radiation	10	53
Inhaled Particulates	0.2	0.2
Inhaled Radon Daughters	360 (530) *	170 (250) *

* Radon daughter doses calculated utilizing equilibrium factors cited by Swedjemark, while values in parentheses derived using equilibrium factors cited by UNSCEAR.

4.1.3 WELL-WATER

DESCRIPTION:

In this scenario, a well is sunk into the tailings for the purpose of obtaining potable water. The well is assumed to be a gravel packed, rotary drilled type of single string construction, having a depth of 5 metres. The inflow of surface water is prevented by suitably sealing the well walls, except for the bottom 25 cm of the shaft which is perforated and covered by a well screen. It is also postulated that all of the yearly intake of water for the exposed individual is obtained from this well. It should be noted that the acceptability of the well water to the individual, with respect to appearance or taste, is considered, on the basis of discussions with Ontario Ministry of the Environment staff, highly suspect. Notwithstanding, the analysis of this scenario was performed recognizing the very low probability of occurrence.

EXPOSURE PATHWAYS:

The only significant exposure pathway is the ingestion of contaminated water.

RADIONUCLIDE CONCENTRATIONS:

Given the complex nature of the chemical interactions in the tailings, it would be very difficult, and beyond the scope of this study, to attempt to develop meaningful models to estimate the concentrations of radioisotopes in the tailings pore water. Accordingly, it was decided to base the analysis of this scenario for Elliot Lake reference tailings site on empirical data from the Nordic site.

Moffett and Tellier (1977) reported on the water quality of 18 test wells on the Nordic site. They found the radionuclide content to vary depending on the location of the well on the tailings and, consequently, they separated the results into two classes; a high acid class and low acid class. The results, given in Table 4.3, show that the radionuclide content to be a function of pH.

As can be observed from Table 4.3, the higher radionuclide content is generally associated with the high-acid class, except for cases where the radioisotope content of the nearby tailings has been depleted.

Accordingly, the radionuclide content of the high-acid class well water is extremely variable and dependent on the situation in the immediate tailings environment close to the location of the well. It is interesting to note that, according to Moffett and Tellier, the low-acid water samples were obtained from the area in the tailings that is composed predominantly of slimes whereas the wells yielding high acid samples are located close to dams or the original point of discharge at the centre of the tailings, where the tailings are much coarser.

Lim and Dave (1978) analyzed water samples, obtained from 3 piezometers located on the Nordic tailings, for pH and dissolved radium-226 content. The water was approximately neutral (pH = 7.18 +- 0.27) with a radium content of 6.3 +- 1.3 Bq/L. Unfortunately, the locations of the test wells were not specified; thus, it was not possible to compare Lim and Dave's data with the data of Moffett and Tellier with any degree of confidence. However, the concentrations of radium in the Moffett low-acid class water samples are reasonably consistent with the radium concentrations in samples analyzed by Lim.

INTRUDER DOSE ESTIMATES:

Doses were calculated both for a high-acid class well, and a low-acid class well. In order to gain an appreciation of the variability of the potential doses, and because of the lack of information, two assumptions were made for the low-acid class wells as data were not available on the thorium-230 concentrations. These are:
(i) the radium-226 is in equilibrium with thorium-230, and,
(ii) the radium-226 content is 10 times that of thorium-230.
The committed effective dose equivalent and committed organ dose equivalents are given in Tables 4.4, 4.5, and 4.6.

Adequate data on the Rabbit Lake Tailings or on other Saskatchewan sites were not available from which to calculate the doses resulting from the well-water scenario for a northern Saskatchewan tailings site. For example, there was no information on the radionuclide concentrations of the tailings pore water. Notwithstanding, it is instructive to observe that a major difference between the Elliott Lake and Rabbit Lake tailings is the very low thorium content of the ore at Rabbit Lake. However, at the Nordic site, the dose received from the ingestion of the thorium-232 series radionuclides is only a small percentage of the total dose (6.1% - 14%). Accordingly, it is not expected that this difference between the tailings sites will impact greatly on the intruder dose resulting from this scenario.

The estimated annual doses are summarized below:

Committed Effective Dose Equivalent for the Elliot Lake reference site:

High acid class	180 mSv
Low acid class (Ra-226 concentration = Th-230)	51 mSv
Low acid class (Ra-226 concentration 10X Th-230)	47 mSv

As explained above, the lack of data for the northern Saskatchewan sites does not permit meaningful estimates of radiation doses resulting from this scenario.

4.2 INTRUDER-AGRICULTURE SCENARIO

4.2.1 GARDENING

DESCRIPTION:

Tailings areas are generally considered non-productive for agricultural activities, as the tailings materials are almost completely depleted of phosphorous and nitrogen. Accordingly, it is not considered feasible that large-scale, commercial farming would be economically viable. However, it is conceivable, though unlikely, that some garden farming could be carried out, by initially preparing the soil appropriately such as with lime addition. Both below ground and above ground produce may be grown, such as leafy vegetables (Swiss chard, beet leaves) and root and stem vegetables (carrots,beets, etc.). It is assumed that the vegetation is equally divided between above ground and below ground vegetation types. Furthermore, in this scenario, due to the expected low productivity of the tailings area, it is assumed that, for the base case, produce harvested from the backyard garden would be at most 30 Kg, or about 25% of the annual consumption of vegetables given in NUREG-0706. Notwithstanding, a range of exposure conditions likely exist and it may be postulated that, in the extreme, the entire 120 Kg of produce consumed annually are grown on the tailings and, hence, the estimated doses must be scaled upwards by a factor of 4.

EXPOSURE PATHWAYS:

The two significant exposure pathways are direct gamma exposure from the tailings material and the ingestion of contaminated food stuffs. Inhalation of radioactive particulates need not be considered for this scenario as it can be reasonably assumed that the tailings are vegetated thereby minimizing fugitive dust emissions. As discussed in Section 3.2.2, exposures to radon daughters are considered to result in negligible doses.

ASSUMED EXPOSURE CONDITIONS:

Exposure time: 240 h/y. (2 h/d x 30 d/m x 4 m/y)

Consumption of contaminated vegetables: 30 Kg/y.

The annual intake of radionuclides from the ingestion of contaminated vegetables is given below. The calculations were based on the methodology described in Section 3.2.3.2.

ANNUAL INTAKE OF RADIONUCLIDES :

	Elliot Lake (Bq)	Northern Saskatchewan (Bq)
U-238-234:	15	520
TH-230:	150	4800
RA-226:	1700	10000
PB-210:	980	4500
PO-210	240	1100
TH-232:	230	48
TH-228	650	48
RA-228:	460	97

INTRUDER DOSE ESTIMATES:

The annual effective dose equivalent and annual committed organ dose equivalent resulting from the ingestion of contaminated vegetables are given in Tables 4.7 and 4.8 for the Elliot Lake tailings sites and Northern Saskatchewan tailings sites respectively.

The resulting uptakes and consequent doses were calculated for the Elliot Lake and northern Saskatchewan reference tailings areas. These are summarized below:

	Committed Effective Dose Equivalent	
PATHWAY	Elliot Lake mSv	Northern Saskatchewan mSv
External Gamma	0.6	3.4
Ingestion of Contaminated vegetables	2.4	11.4

The dose estimates above are calculated based on the assumption, that 30 Kg of contaminated produce are consumed annually. If, however, the annual intake of contaminated produce was, in fact, 120 Kg per year, then the estimated doses would increase to approximately 10 mSv on the Elliot Lake tailings and 45 mSv on the northen Saskatchewan tailings.

It is also worth noting that, from the above, the ingestion pathway contributes the major portion of the dose. As mentioned in Section 3.2.3.1, the new information being developed by Kalin suggests that the soil to plant transfer parameters are significantly larger than those used in Beak (1983b). This will consequently result in estimates of larger radiation doses to the intruder.

4.2.2 CATTLE RAISING

DESCRIPTION:

In this scenario, it is assumed that the tailings are vegetated and that the cattle will acquire all of their intake of grass from eating the pasture vegetation on the tailings area. It is further assumed that this represents half of their diet, the other half made up of

forage from non-contaminated areas. For modelling purposes, it is postulated that all of the individual's meat diet of 80 kg/yr (See Section 3.2.3.3) is obtained from consuming this cattle. Although it dose not appear likely, because of the poor productivity of the tailings, that the tailings will be used for grazing dairy cattle, the potential doses,resulting from this exposure pathway, are discussed in this section.

EXPOSURE PATHWAYS

The two significant exposure pathways are direct gamma exposure from the tailings material, and the ingestion of radioactivity from the contaminated meat. The inhalation of radioactive particulates need not be considered as the tailings would be vegetated.

ASSUMED EXPOSURE CONDTIONS

Exposure time: 60 hr/y = 0.5 hr/d x 30 d/m x 4 m/y. (The exposure times, assumed for this scenario, were based on the input from three farmers engaged in raising cattle.)

Consumption of contaminated Meat: 80 kg/y

Annual Intake of Radionuclides:

	Elliot Lake (Bq)	Northern Saskatchewan (Bq)
U-238-234:	20	700
Th-230:	200	6400
Ra-226:	4800	27000
Pb-210:	9000	43000
Po-210:	320	1500
Th-232:	300	64
Th-228:	870	64
Ra-228:	1300	270

INTRUDER DOSE ESTIMATES:

The annual effective dose equilvalent and committed organ dose equivalent resulting from the ingestion of contaminated meat are given in Tables 4.9 and 4.10 for the Elliot Lake and Northern Saskatchewan tailings areas respectively.

The doses received by the intruder are summarized below:

	Effective Dose Equivalent	
	Elliot Lake	Northern Saskatchewan
	mSv	mSv
External Gamma	0.15	0.85
Ingestion of contaminated meat	16.	73

From the above it can be observed that the ingestion of contaminated meat contributes almost the entire dose resulting from this intrusion scenario.
Although, as mentioned above, the tailings do not afford a good environment for raising dairy cattle, the doses arising from the ingestion of contaminated milk will be slightly less (35%) than the doses resulting from eating contaminated meat. (This result is obtained from considering the annual ingestion of milk compared to meat and the transfer parameters from feed to milk for Pb-210 compared to that for feed to meat. Only, one isotope, Pb-210 need be considered for this purpose, as Pb-210 contributes between 82% and 85% of the ingestion dose.)

4.3 INTRUDER-CONSTRUCTION SCENARIO

4.3.1 ROAD

DESCRIPTION:

In this scenario, it is assumed that a two lane ashphalt road is constructed across the longest dimension of the Nordic Tailings which measures approximately 1.6 km in length. As the water table is only 1 or 2 metres below the surface, supporting structures for the road will have to be built. Accordingly, based on advice from Ontario Ministry of Transport personnel, it is assumed that the construction will take a minimum of 3 months with most of the work occurring in the frost-free period of the year. Furthermore, it is assumed that dust control measures such as spraying with calcium chloride will not be initiated due to the remote location of the tailings.

EXPOSURE PATHWAYS:

The two exposure pathways of significance are exposure to gamma radiation from the tailings and exposure to radioactive particulates.

RADIATION FIELDS AND RADIONUCLIDE CONCENTRATIONS:

	Elliot Lake	Northern Saskatchewan
Gamma Dose Rates (uSv/h):	2.5	18

(Shielding factor = 0.7; uneven ground during construction, see Section 3.2.4.1.)

Airborne Particulate Concentrations (mg/m^3):

	Elliot Lake	Northen Saskatchewan
High Activity	1000	50
Low Activity	50	10

Radionuclide Concentrations:

	Elliot Lake		Northern Saskatchewan	
	Low Act mBq/m^3	High Act mBq/m^3	Low Act mBq/m^3	High Act mBq/m^3
U-238-234	0.010	0.20	0.070	0.35
Th-230	0.060	1.2	0.38	1.9
Ra-226	0.33	6.7	0.38	1.9
Pb-210	0.41	8.1	0.38	1.9
Po-210	0.41	8.1	0.38	1.9
Th-232	0.090	1.8	0.0038	0.019
Th-228	0.259	5.2	0.0038	0.019
Ra-228	0.090	1.8	0.0038	0.019

ASSUMED EXPOSURE CONDITIONS:

Exposure Time: 600 hours (10 h/d x 20 d/m x 3 m). Percentage of time in high concentration of particulates: 25%, remainder of time (75%) in low concentration.

Inhalation Rates (See Section 3.2.1): 50% of time performing heavy work (2.63 m^3/h)
:50% of time performing normal activity (0.96 m^3/h)

INTRUDER DOSE ESTIMATES:

The committed organ dose equivalents and the committed effective dose equivalent resulting from inhaled particulates are given in Tables 4.11 and 4.12 for the Elliot Lake and Northen Saskatchewan sites respectively. The doses are summarized below:

	Effective Dose Equivalent	
	Elliot Lake	Northern Saskatchewan
	mSv	mSv
External gamma	1.5	8.7
Inhaled particulates	0.4	0.07

Although it is recognized that there is considerable uncertainty in specifying the exposure conditions and that a range of conditions may apply, it is worthy of note that the pathway that contributes the larger fraction of the dose is the external gamma. Even assuming an unrealistic exposure condition, that the worker spends all of his time performing heavy work while on site, the dose from inhalation will remain less than 50% of the external gamma dose at the Elliot Lake site and less than 20% of the external gamma dose at the Northern Saskatchewan site.

4.3.2 EXCAVATION

Description:

In this scenario, it is assumed that an intruder will excavate the tailings for use at a location away from the tailings, primarily for construction materials. The scope of this analysis includes only evaluating the radiation exposure that the person receives while physically on the tailings area. The modelling of this scenario is similiar to that for road building as both scenarios involve heavy labour and disturbing the tailings thereby producing elevated levels of fugitive dust emissions. The most significant difference between the road building scenario and the excavation scenario, is in the assumed exposure conditions. For the excavation scenario, the labourer is assumed to be in the high dust airborne concentrations for extended periods of time whereas the intruder constructing the road would be involved in a variety of activities other than excavation. Accordingly, the labourer may well spend a significant proportion of his time under conditions where the airborne dust concentrations are assumed to be significantly lower.

EXPOSURE PATHWAYS:

The major exposure pathways are:
-- external exposure to gamma radiation, and
-- internal exposure from the inhalation of radioactive particulates.

RADIATION FIELD LEVELS AND RADIONUCLIDE CONCENTRATIONS:

These will be the same as in the road construction scenario; Section 4.4.1.

ASSUMED EXPOSURE CONDITIONS:

Exposure Duration: 600 hours. Fraction of time in high particulate concentrations is 75%, while 25% of the time is in low concentrations. These exposure conditions are believed to be realistic, however, as a range of conditions is feasable, the effect on the estimated dose to the intruder is analyzed.

INTRUDER DOSE ESTIMATES:

	Effective Dose Equivalent	
	Elliot Lake (mSv)	Northen Saskatchewan (mSv)
External gamma	1.5	8.7
Inhaled particulates	1.0	1.6

The variation of total effective dose equivalent with assumed fraction of time exposed to high levels of radioactive particulates is shown in Figure 4.1. This graph demonstrates that the total dose does not change by more than a factor of 2 regardless of the percentage of time the intruder is assumed to be exposed to different levels of particulate contamination.

4.4 INTRUDER - RECREATION SCENARIO

4.4.1 CAMPING

DESCRIPTION:

Intrusion recreational activities include camping, hunting, golfing, etc. (Golfing on the Beaverlodge tailings was a popular pastime.) These intrusions do not result in alteration of the tailings; consequently the radiation fields and the magnitudes of the releases of radioactivity for this scenario may be assumed to approximate the levels encountered during normal environmental conditions. Accordingly, the doses calculated for an intruder camping on the tailings may be used to determine the doses to a person performing any recreational activity, which does not disturb the tailings, by simply prorating the doses by the exposure times. With respect to the camping scenario, it is assumed that the person camps for a period of one month per year. During this period, it is assumed that he will spend 8 hours per day sleeping on the ground and the remaining time performing other activities on the tailings.

EXPOSURE PATHWAYS:

The two significant exposure pathways are direct gamma exposure and the inhalation of radioactive particulates.

RADIATION FIELD LEVELS AND RADIONUCLIDE CONCENTRATIONS:

	Elliot Lake	Northern Saskatchewan
Gamma Dose Rates:		
Standing position (uGy/h)	3.6	26
(Shielding factor = 1)		
Sleeping position (uGy/h)	5.4	38
(Dose rate at nominal contact with ground 1.5 times that at 1 metre: Derived from data in Slade (1968).		
Airborne Particulates Concentrations		
Dust Loading (ug/m^3)	30	10
Radionuclide concentrations:	(mBq/m^3)	(mBq/m^3)
U-238-234	0.006	0.070
Th-230	0.035	0.38
Ra-226	0.20	0.38
Pb-210	0.24	0.38
Po-210	0.24	0.38
Th-232	0.054	0.0038
Th-228	0.16	0.0038
Ra-228	0.054	0.0038

ASSUMED EXPOSURE CONDITIONS:

Exposure Time: 720 hours; 67% of time in standing position, 33% of time in sleeping or crouching position.

Breathing Rates: 0.96 m^3/h 67% of time; 0.8 m^3/h 33% of time.

INTRUDER DOSE ESTIMATES:

The annual committed effective dose equivalent and the annual committed organ dose equivalents resulting from the intake of radioactive particulates are given in Tables 4.13 and Table 4.14 for the Elliot Lake and Northern Saskatchewan sites respectively. The doses are summarized below:

	Effective Dose Equivalent	
	Elliot Lake (mSv)	Northern Saskatchewan (mSv)
External Gamma	3.1	17
Inhaled Particulates	0.024	0.023

4.4.2 RACING

DESCRIPTION:

From discussions with local residents of the Kirkland Lake gold mining area, ad-hoc automobile racing on the tailings appears to be a popular recreational activity. For the purpose of this study, it is assumed that the intruder races during the summer period, and has the car windows open and maintains the inhalation rate of the labourer performing heavy work. Based on the experience at Kirkland Lake, it may be assumed that a person will participate in ad-hoc racing for a period of 2 hours per day during weekends, and that one person may perform this activity on an average of 10 times a year. In addition to autmobile racing, it may be postulated that motorcycle racing is also practiced on tailings. The differences with respect to the estimated doses to the intruders performing motorcycle racing to those racing automobiles are discussed. Also, the dose arising from driving a snowmobile on the tailings is determined.

EXPOSURE PATHWAYS:

The two significant exposure pathways are direct gamma exposure from the tailings material and inhalation of radioactive particulates.

RADIATION FIELD LEVELS AND RADIONUCLIDE CONCENTRATIONS

	Elliot Lake	Northern Saskatchewan
Gamma dose rates (uGy/h):	1.8	2.3

(Shielding factor of 0.5 applied; for discussion see Section 4.2.3).

Airborne Particulates Concentrations:		
Dust Loading (ug/m^3)	1000	50

Radionuclide Concentrations:	(mBq/m^3)	(mBq/m^3)
U-234-238:	0.020	0.17
Th-230:	1.2	0.65
Ra-226:	6.7	0.43
Pb-210:	8.0	0.63
Po-210:	8.0	0.63
Th-232:	1.8	0.003
Th-228:	5.2	0.003
Ra-228:	1.8	0.003

ASSUMED EXPOSURE CONDITIONS:

Exposure time: 20 hours per year
Inhalation rate: 2.6 m^3/h

INTRUDER DOSE ESTIMATE:

The annual committed effective dose equivalent and the annual committed organ dose equivalents resulting from the inhalation of radioactive particulates are given in Table 4.15 and 4.16 for the Elliot Lake and Northern Saskatchewan sites respectively. The doses are summarized below:

	Effective Dose Equivalent	
	Elliot Lake	Northern Saskatchewan
	(mSv)	(mSv)
External gamma	0.029	0.21
Inhaled particulates	0.062	0.008

The difference in the dose estimates for the motorcycle racer and the automobile racer arises in the external gamma exposure pathway. The automobile provides the occupant with some shielding; the shielding factor having been estimated to be 0.5 (Section 3.2.4). The motorcycle racer will not receive the same degree of shielding and in the worse case it may be assumed that the shielding factor equals 1. This results in the doubling of the external gamma dose to 0.058 mSv for the Elliot Lake site and 0.42 mSv for the Northern Saskatchewan site.

The dose incurred by the snowmobile operator will arise solely from the external gamma exposure pathway, as the snow cover will eliminate any particulate releases. The shielding afforded by the snowmobile is assumed to approximate that of the automobile, accordingly, the dose is estimated to be 0.029 mSv to the intruder on the Elliot Lake tailings and 0.021 mSv on the Northern Saskatchewan tailings.

4.4.3 SWIMMING

DESCRIPTION:

Although unlikely, it is conceivable that an intruder might swim in a contaminated tailings pond that is an integral part of the tailings system. It is assumed for this scenario that sufficiently large areas

of the reference tailings sites are water covered for this type of intrusion to be possible.

EXPOSURE PATHWAYS:

The only significant exposure pathway is external beta-gamma exposure.

RADIONUCLIDE CONCENTRATIONS:

For the purpose of modelling, the concentrations of the radionuclides in the discharge, upstream from any treatment facility such as a barium chloride addition station, is considered to be the concentrations of radionuclides in the water to which the person will be exposed. The radioisotope levels in the tailings water cover at the Nordic site and the Rabbit Lake site will be used to model this scenario. The average radium concentration in the tailings pond at the Nordic tailings is approximately 0.75 Bq/L (MacLaren, 1978b) while the concentrations in Rabbit Lake pond range typically from 15 to 20 Bq/L (Pun,1985). Unfortunately, with the exception of Ra-226, data are lacking on the other radionuclide concentrations in the Nordic and Rabbit Lake discharges. However, as can be seen from Table 3.1, each radionuclide of the uranium-238 chain other than Ra-226 contributes from 2 orders to 5 orders less to the effective dose equivalent (whole body dose) than does radium-226 (including short-lived daughters) per unit concentration. The major contributor to skin dose is also from Ra-226 (including short-lived daughters). Although the thorium-232 nuclides contribute approximately the same level of exposures per unit concentration as radium-226, from data on the Quirke Tailings effluent (MacLaren,1978b), it appears that the thorium-232, thorium-228 and radium-228 concentrations are at least a factor of 10 less than the radium-226 concentration. In the absence of empirical data, the thorium-232 series radionuclide levels in the Rabbit Lake tailings pond are assumed to be 1% of the uranium-238 series. Data from tailings areas in Elliot Lake and northern Saskatchewan are required to validate the appropriateness of the above assumptions on the radionuclide concentrations for both reference sites. Based on the arguments presented above, the radionuclide concentrations in the Elliot Lake and Northern Saskatchewan tailings ponds are estimated to be as follows:

Radionuclide Concentrations

	Elliot Lake (Bq/L)	Northern Saskatchewan (Bq/L)
Uranium-238-234:	0.75	20
Thorium-230:	0.75	20
Radium-226:	0.75	20
Lead-210:	0.75	20
Polonium-210:	0.75	20
Thorium-232:	0.075	0.2
Thorium-228:	0.075	0.2
Radium-228:	0.075	0.2

ASSUMED EXPOSURE CONDITIONS:

Exposure Duration: 30 hours per year (Beak,1983b)

INTRUDER DOSE ESTIMATE:

The effective dose equivalent and dose to tissues at 70 um depth (skin dose) received by an intruder swimming in contaminated ponds are detailed in Tables 4.17 and 4.18 for the Elliot Lake site and Northern Saksatchewan site respectively. The doses are summarized below:

	Elliot Lake (uSv)	Northern Saksatchewan (uSv).
Whole Body EDE	6.0	150
Skin Dose Equivalent	11	280

Figure 4.2 demonstrates the dependence of the effective dose equivalent on the ratio of the level of the thorium-232 series radionuclides compared to those of the uranium-238 series. This figure demonstrates, that for variations of the ratios of the radionuclide concentrations between 1% and 50%, the effective dose equivalent does not change by more than a factor of 2.

TABLE 4.1

ANNUAL INTAKE OF RADIONUCLIDES AND ANNUAL COMMITTED DOSE EQUIVALENT VIA INHALATION RECEIVED BY INTRUDER INHABITING A HUT ON THE ELLIOT LAKE REFERENCE TAILINGS SITE. DOSES ARE EXPRESSED IN SIEVERTS.

NUCLIDE	ACT(PCI)	ACT (BQ)	GONADS	BREAST	R MARROW	LUNGS	THYROID	ENDOSTEAL	REMAIND	EFF DE
U-238-Y	.46	.01702	4.12E-11	4.95E-11	1.171E-9	4.527E-6	4.65E-11	1.719E-8	1.636E-9	5.446E-7
U-238-W	.46	.01702	1.14E-10	1.15E-10	3.370E-9	2.417E-7	1.14E-10	5.004E-8	4.323E-9	3.234E-8
U-234-Y	.46	.01702	4.51E-11	4.56E-11	1.229E-9	5.072E-6	4.51E-11	1.923E-8	1.838E-9	6.093E-7
U-234-W	.46	.01702	1.28E-10	1.28E-10	3.574E-9	2.723E-7	1.28E-10	5.600E-8	4.851E-9	3.625E-8
TH-230	5.5	.2035	3.500E-8	3.500E-8	1.422E-5	6.125E-5	3.500E-8	1.772E-4	9.117E-8	1.439E-5
RA-226	30.8	1.1396	1.162E-7	1.162E-7	7.567E-7	1.835E-5	1.162E-7	8.650E-6	1.219E-7	2.644E-6
PB-210	37.3	1.3801	4.389E-7	4.389E-7	5.175E-6	4.389E-7	4.389E-7	7.549E-5	6.473E-6	5.065E-6
PO-210	37.3	1.3801	5.576E-7	5.576E-7	5.576E-7	1.006E-6	5.576E-7	5.576E-7	1.021E-5	3.505E-6
TOT U			1.148E-6	1.148E-6	2.072E-5	9.116E-5	1.148E-6	2.621E-4	1.691E-5	2.682E-5
TH-232	8.3	.3071	1.836E-7	1.886E-7	1.231E-4	2.887E-4	1.840E-7	.0015324	4.637E-7	9.551E-5
TH-228	23.9	.8843	1.999E-7	2.052E-7	1.654E-5	6.111E-4	2.034E-7	2.025E-4	5.350E-7	8.162E-5
RA-228	8.3	.3071	5.620E-8	5.651E-8	2.266E-7	2.217E-6	5.620E-8	1.999E-6	5.743E-8	3.962E-7
TOT TH			4.397E-7	4.502E-7	1.399E-4	9.019E-4	4.435E-7	.0017369	1.056E-6	1.775E-4
TOTAL			1.588E-6	1.598E-6	1.606E-4	9.931E-4	1.592E-6	.0019990	1.797E-5	2.043E-4

TABLE 4.2

ANNUAL INTAKE OF RADIONUCLIDES AND ANNUAL COMMITTED DOSE EQUIVALENT VIA INHALATION RECEIVED BY INTRUDER INHABITING A HUT ON THE NORTHERN SASKATCHEWAN REFERENCE TAILINGS SITE. DOSES ARE EXPRESSED IN SIEVERTS.

NUCLIDE	ACT(PCI)	ACT (BQ)	GONADS	BREAST	R MARROW	LUNGS	THYROID	ENDOSTEAL	REMAIND	EFF DE
U-238-Y	5.4	.1998	4.84E-10	5.81E-10	1.375E-8	5.315E-5	5.45E-10	2.018E-7	1.920E-8	6.394E-6
U-238-W	5.4	.1998	1.341E-9	1.347E-9	3.956E-8	2.837E-6	1.341E-9	5.874E-7	5.075E-8	3.796E-7
U-234-Y	5.4	.1998	5.29E-10	5.35E-10	1.443E-8	5.954E-5	5.29E-10	2.258E-7	2.158E-8	7.153E-6
U-234-W	5.4	.1998	1.502E-9	1.502E-9	4.196E-8	3.197E-6	1.502E-9	6.573E-7	5.694E-8	4.256E-7
TH-230	57	2.109	3.627E-7	3.627E-7	1.474E-4	6.348E-4	3.627E-7	.0018369	9.448E-7	1.491E-4
RA-226	57	2.109	2.151E-7	2.151E-7	1.400E-6	3.395E-5	2.151E-7	1.601E-5	2.257E-7	4.893E-6
PB-210	57	2.109	6.707E-7	6.707E-7	7.909E-6	6.707E-7	6.707E-7	1.154E-4	9.891E-6	7.740E-6
PO-210	57	2.109	8.520E-7	8.520E-7	8.520E-7	1.537E-6	8.520E-7	8.520E-7	1.561E-5	5.337E-6
TOT U			2.104E-6	2.105E-6	1.577E-4	7.897E-4	2.104E-6	.0019708	2.682E-5	1.814E-4
TH-232	.57	.02109	1.261E-8	1.295E-8	8.457E-6	1.982E-5	1.263E-8	1.052E-4	3.185E-8	6.559E-6
TH-228	.57	.02109	4.766E-9	4.893E-9	3.944E-7	1.457E-5	4.851E-9	4.830E-6	1.276E-8	1.947E-6
RA-228	.57	.02109	3.859E-9	3.881E-9	1.536E-8	1.523E-7	3.859E-9	1.373E-7	3.944E-9	2.721E-8
TOT TH			2.124E-8	2.172E-8	8.867E-6	3.455E-5	2.134E-8	1.102E-4	4.855E-8	8.533E-6
TOTAL			2.126E-6	2.126E-6	1.666E-4	8.242E-4	2.126E-6	.0020810	2.687E-5	1.900E-4

TABLE 4.3

RADIONUCLIDE CONTENT OF WELL WATER SAMPLES FROM NORDIC TAILINGS

	Bq/L					ug/L
Class	Ra-226	Th-230	Pb-210	Th-232	Th-228	U
Low-Acid	4.2+-1.0	na	2.0+-.9	na	< 0.56	247+- 181
High-Acid	2.2+-1.6	527+-818	6.4+-6.7	43+-66	15+-28	327+-524

na - Data not provided.

Data derived from Moffett (1977).

TABLE 4.4

ANNUAL INTAKE OF RADIONUCLIDES AND ANNUAL COMMITTED DOSE EQUIVALENT VIA INGESTION RECEIVED BY INTRUDER CONSUMING WATER FROM A WELL SUNK INTO THE ELLIOT LAKE REFERENCE TAILINGS SITE. HIGH ACID CASE. DOSES ARE EXPRESSED IN SIEVERTS.

NUCLIDE	ACT(PCI)	ACT (BQ)	GONADS	BREAST	R MARROW	LUNGS	THYROID	ENDOSTEAL	REMAIND	EFF DE
U-238-I	1100000	40700	4.151E-6	3.797E-6	1.107E-4	3.753E-6	3.744E-6	.0016443	6.553E-4	2.613E-4
U-238-S	1100000	40700	9.402E-5	9.402E-5	.0027676	9.361E-5	9.361E-5	.041107	.0039438	.0028002
U-234-I	1100000	40700	4.314E-6	4.192E-6	1.172E-4	4.192E-6	4.192E-6	.0018396	7.204E-4	2.873E-4
U-234-S	1100000	40700	1.054E-4	1.050E-4	.0029345	1.050E-4	1.050E-4	.045991	.0044363	.0031176
TH-230	10000000	370000	2.523E-4	.0002516	.10693	.0002516	.0002516	1.295	.005698	.05476
RA-226	37000	1369	1.254E-4	1.255E-4	8.187E-4	1.254E-4	1.253E-4	.0093503	1.410E-4	4.901E-4
PB-210	1300000	48100	.0060125	.0060125	.071188	.0060125	.0060125	1.03896	.088985	.069745
PO-210	1300000	48100	.0039586	.0039586	.0039586	.0039586	.0039586	.0039586	.073112	.0247234
	0									
TOT U			.0105568	.0105553	.1888253	.0105547	.0105545	2.437851	.1776918	.1561849
TH-232	850000	31450	3.931E-5	3.963E-5	.046546	3.931E-5	3.805E-5	.581825	4.623E-4	.0232101
TH-228	850000	31450	7.957E-5	7.328E-5	.0060699	7.265E-5	7.234E-5	.0745365	.0012140	.0033652
RA-228	37000	1369	2.163E-4	2.149E-4	8.940E-4	2.149E-4	2.149E-4	.0079676	2.231E-4	5.312E-4
TOT TH			3.352E-4	3.278E-4	.0535098	3.269E-4	3.253E-4	.6643291	.0018994	.0271064
TOTAL			.0108919	.0108831	.2423351	.0108816	.0108799	3.102180	.1795912	.1832913

TABLE 4.5

ANNUAL INTAKE OF RADIONUCLIDES AND ANNUAL COMMITTED DOSE EQUIVALENT VIA INGESTION RECEIVED BY INTRUDER CONSUMING WATER FROM A WELL SUNK INTO THE ELLIOT LAKE REFERENCE TAILINGS SITE. LOW ACID CASE: [RA] = [TH]. DOSES ARE EXPRESSED IN SIEVERTS.

NUCLIDE	ACT(PCI)	ACT (BQ)	GONADS	BREAST	R MARROW	LUNGS	THYROID	ENDOSTEAL	REMAIND	EFF DE
U-238-I	29000	1073	1.094E-7	1.001E-7	2.919E-6	9.893E-8	9.872E-8	4.335E-5	1.728E-5	6.889E-6
U-238-S	29000	1073	2.479E-6	2.479E-6	7.296E-5	2.468E-6	2.468E-6	.0010837	1.040E-4	7.382E-5
U-234-I	29000	1073	1.137E-7	1.105E-7	3.090E-6	1.105E-7	1.105E-7	4.850E-5	1.899E-5	7.575E-6
U-234-S	29000	1073	2.779E-6	2.768E-6	7.736E-5	2.768E-6	2.768E-6	.0012125	1.170E-4	8.219E-5
TH-230	80000	2960	2.019E-6	2.013E-6	8.554E-4	2.013E-6	2.013E-6	.01036	4.538E-5	4.381E-4
RA-226	80000	2960	2.711E-4	2.714E-4	.0017701	2.711E-4	2.708E-4	.0202168	3.049E-4	.0010597
PB-210	40000	1480	.000185	.000185	.0021904	.000185	.000185	.031968	.002738	.002146
PO-210	40000	1480	1.218E-4	1.218E-4	1.218E-4	1.218E-4	1.218E-4	1.218E-4	.0022496	7.607E-4
	0									
TOT U			5.854E-4	5.857E-4	.0050941	5.854E-4	5.851E-4	.0650547	.0055953	.0045750
TH-232	11000	407	5.088E-7	5.128E-7	6.024E-4	5.088E-7	4.925E-7	.0075295	5.983E-6	3.004E-4
TH-228	11000	407	1.030E-6	9.483E-7	7.855E-5	9.402E-7	9.361E-7	9.646E-4	1.571E-5	4.355E-5
RA-228	11000	407	6.431E-5	6.390E-5	2.658E-4	6.390E-5	6.390E-5	.0023687	6.634E-5	1.579E-4
TOT TH			6.584E-5	6.536E-5	9.467E-4	6.535E-5	6.533E-5	.0108628	9.803E-5	5.018E-4
TOTAL			6.513E-4	6.511E-4	.0060407	6.507E-4	6.504E-4	.0759175	.0056833	.0050768

TABLE 4.6

ANNUAL INTAKE OF RADIONUCLIDES AND ANNUAL COMMITTED DOSE EQUIVALENT VIA INGESTION RECEIVED BY INTRUDER CONSUMING WATER FROM A WELL SUNK INTO THE ELLIOT LAKE REFERENCE TAILINGS SITE. LOW ACID CASE: [RA] = 10 X [TH]. DOSES ARE EXPRESSED IN SIEVERTS.

NUCLIDE	ACT(PCI)	ACT (BQ)	GONADS	BREAST	R MARROW	LUNGS	THYROID	ENDOSTEAL	REMAIND	EFF DE
U-238-I	29000	1073	1.094E-7	1.001E-7	2.919E-6	9.893E-8	9.872E-8	4.335E-5	1.728E-5	6.889E-6
U-238-S	29000	1073	2.479E-6	2.479E-6	7.296E-5	2.468E-6	2.468E-6	.0010837	1.040E-4	7.382E-5
U-234-I	29000	1073	1.137E-7	1.105E-7	3.090E-6	1.105E-7	1.105E-7	4.850E-5	1.899E-5	7.575E-6
U-234-S	29000	1073	2.779E-6	2.768E-6	7.736E-5	2.768E-6	2.768E-6	.0012125	1.170E-4	8.219E-5
TH-230	8000	296	2.019E-7	2.013E-7	8.554E-5	2.013E-7	2.013E-7	.001036	4.558E-6	4.381E-5
RA-226	80000	2960	2.711E-4	2.714E-4	.0017701	2.711E-4	2.708E-4	.0202168	3.049E-4	.0010597
PB-210	40000	1480	.000185	.000185	.0021904	.000185	.000185	.031968	.002738	.002146
PO-210	40000	1480	1.218E-4	1.218E-4	1.218E-4	1.218E-4	1.218E-4	1.218E-4	.0022496	7.607E-4
	0									
TOT U			5.836E-4	5.839E-4	.0043242	5.836E-4	5.833E-4	.0557307	.0055542	.0041807
TH-232	11000	407	5.088E-7	5.128E-7	6.024E-4	5.088E-7	4.925E-7	.0075295	5.983E-6	3.004E-4
TH-228	11000	407	1.030E-6	9.483E-7	7.855E-5	9.402E-7	9.361E-7	9.646E-4	1.571E-5	4.355E-5
RA-228	11000	407	6.431E-5	6.390E-5	2.658E-4	6.390E-5	6.390E-5	.0023687	6.634E-5	1.579E-4
TOT TH			6.584E-5	6.536E-5	9.467E-4	6.533E-5	6.533E-5	.0108628	8.803E-5	5.013E-4
TOTAL			6.493E-4	6.493E-4	.0052708	6.489E-4	6.486E-4	.0665935	.0056423	.0046825

TABLE 4.7

ANNUAL INTAKE OF RADIONUCLIDES AND ANNUAL COMMITTED DOSE EQUIVALENT VIA INGESTION RECEIVED BY INTRUDER CONSUMING PRODUCE GROWN ON THE ELLIOT LAKE REFERENCE TAILINGS SITE. DOSES ARE EXPRESSED IN SIEVERTS.

NUCLIDE	ACT(PCI)	ACT (BQ)	GONADS	BREAST	R MARROW	LUNGS	THYROID	ENDOSTEAL	REMAIND	EFF DE
U-238-I	203	7.511	7.66E-10	7.01E-10	2.043E-8	6.93E-10	6.91E-10	3.034E-7	1.209E-7	4.822E-8
U-238-S	203	7.511	1.735E-8	1.735E-8	5.107E-7	1.728E-8	1.728E-8	7.586E-6	7.278E-7	5.168E-7
U-234-I	203	7.511	7.96E-10	7.74E-10	2.163E-8	7.74E-10	7.74E-10	3.395E-7	1.329E-7	5.303E-8
U-234-S	203	7.511	1.945E-8	1.938E-8	5.415E-7	1.938E-8	1.938E-8	8.487E-6	8.187E-7	5.753E-7
TH-230	4082	151.034	1.030E-7	1.027E-7	4.365E-5	1.027E-7	1.027E-7	5.286E-4	2.326E-6	2.235E-5
RA-226	46130	1706.81	1.563E-4	1.565E-4	.0010207	1.563E-4	1.562E-4	.0116575	1.758E-4	6.110E-4
PB-210	26244	971.028	1.214E-4	1.214E-4	.0014371	1.214E-4	1.214E-4	.0209742	.0017964	.0014080
PO-210	6561	242.757	1.998E-5	1.998E-5	1.998E-5	1.998E-5	1.998E-5	1.998E-5	3.690E-4	1.248E-4
	0									
TOT U			2.978E-4	2.980E-4	.0025225	2.978E-4	2.977E-4	.0331970	.0023453	.0021674
TH-232	6123	226.551	2.832E-7	2.855E-7	3.353E-4	2.832E-7	2.741E-7	.0041912	3.330E-6	1.672E-4
TH-228	17690	654.53	1.656E-6	1.525E-6	1.263E-4	1.512E-6	1.505E-6	.0015512	2.526E-5	7.003E-5
RA-228	12393	458.541	7.245E-5	7.199E-5	2.994E-4	7.199E-5	7.199E-5	.0026687	7.474E-5	1.779E-4
TOT TH			7.439E-5	7.380E-5	7.610E-4	7.379E-5	7.377E-5	.0084111	1.033E-4	4.151E-4
TOTAL			3.722E-4	3.718E-4	.0032836	3.716E-4	3.714E-4	.0416082	.0024487	.0025825

TABLE 4.8

ANNUAL INTAKE OF RADIONUCLIDES AND ANNUAL COMMITTED DOSE EQUIVALENT VIA INGESTION RECEIVED BY INTRUDER CONSUMING PRODUCE GROWN ON THE NORTHERN SASKATCHEWAN REFERENCE TAILINGS SITE. DOSES ARE EXPRESSED IN SIEVERTS.

NUCLIDE	ACT(PCI)	ACT (BQ)	GONADS	BREAST	R MARROW	LUNGS	THYROID	ENDOSTEAL	REMAIND	EFF DE
U-238-I	7087	262.219	2.675E-8	2.447E-8	7.132E-7	2.418E-8	2.412E-8	1.059E-5	4.222E-6	1.683E-6
U-238-S	7087	262.219	6.057E-7	6.057E-7	1.783E-5	6.031E-7	6.031E-7	2.648E-4	2.541E-5	1.804E-5
U-234-I	7087	262.219	2.780E-8	2.701E-8	7.552E-7	2.701E-8	2.701E-8	1.185E-5	4.641E-6	1.851E-6
U-234-S	7087	262.219	6.791E-7	6.765E-7	1.891E-5	6.765E-7	6.765E-7	2.963E-4	2.858E-5	2.009E-5
TH-230	129276	4783.212	3.262E-6	3.253E-6	.0013823	3.253E-6	3.253E-6	.0167412	7.366E-5	7.079E-4
RA-226	261628	9680.236	8.867E-4	8.877E-4	.0057888	8.867E-4	8.857E-4	.0661160	9.971E-4	.0034655
PB-210	123120	4555.44	5.694E-4	5.694E-4	.0067421	5.694E-4	5.694E-4	.0983975	.0084276	.0066054
PO-210	30780	1138.86	9.373E-5	9.373E-5	9.373E-5	9.373E-5	9.373E-5	9.373E-5	.0017311	5.854E-4
	0									
TOT U			.0015545	.0015554	.0140451	.0015545	.0015535	.1819321	.0112922	.0114059
TH-232	1292	47.804	5.976E-8	6.023E-8	7.075E-5	5.976E-8	5.784E-8	8.844E-4	7.027E-7	3.529E-5
TH-228	1292	47.804	1.209E-7	1.114E-7	9.226E-6	1.104E-7	1.099E-7	1.133E-4	1.845E-6	5.115E-6
RA-228	2614	96.718	1.528E-5	1.518E-5	6.316E-5	1.518E-5	1.518E-5	5.629E-4	1.577E-5	3.753E-5
TOT TH			1.546E-5	1.536E-5	1.431E-4	1.535E-5	1.535E-5	.0015606	1.831E-5	7.792E-5
TOTAL			.0015699	.0015708	.0141882	.0015698	.0015688	.1834926	.0113105	.0114838

TABLE 4.9

ANNUAL INTAKE OF RADIONUCLIDES AND ANNUAL COMMITTED DOSE EQUIVALENT VIA INGESTION RECEIVED BY INTRUDER CONSUMING BEEF CATTLE WHICH HAD GRAZED ON THE ELLIOT LAKE REFERENCE TAILINGS SITE. DOSES ARE EXPRESSED IN SIEVERTS.

NUCLIDE	ACT(PCI)	ACT (BQ)	GONADS	BREAST	R MARROW	LUNGS	THYROID	ENDOSTEAL	REMAIND	EFF DE
U-238-I	270	9.99	1.019E-9	9.32E-10	2.717E-8	9.21E-10	9.19E-10	4.036E-7	1.608E-7	6.414E-8
U-238-S	270	9.99	2.308E-8	2.308E-8	6.793E-7	2.298E-8	2.298E-8	1.009E-5	9.680E-7	6.873E-7
U-234-I	270	9.99	1.059E-9	1.029E-9	2.877E-8	1.029E-9	1.029E-9	4.515E-7	1.768E-7	7.053E-8
U-234-S	270	9.99	2.587E-8	2.577E-8	7.203E-7	2.577E-8	2.577E-8	1.129E-5	1.089E-6	7.652E-7
TH-230	5440	201.28	1.373E-7	1.369E-7	5.817E-5	1.369E-7	1.369E-7	7.045E-4	3.100E-6	2.979E-5
RA-226	130200	4817.4	4.413E-4	4.418E-4	.0028808	4.413E-4	4.408E-4	.0329028	4.962E-4	.0017246
PB-210	244900	9061.3	.0011327	.0011327	.0134107	.0011327	.0011327	.1957241	.0167634	.0131389
PO-210	8700	321.9	2.649E-5	2.649E-5	2.649E-5	2.649E-5	2.649E-5	2.649E-5	4.893E-4	1.655E-4
	0									
TOT U			.0016006	.0016011	.0163776	.0016006	.0016001	.2293801	.0177544	.0150603
TH-232	8200	303.4	3.793E-7	3.823E-7	4.490E-4	3.793E-7	3.671E-7	.0056129	4.460E-6	2.239E-4
TH-228	23600	873.2	2.209E-6	2.035E-6	1.685E-4	2.017E-6	2.008E-6	.0020695	3.371E-5	9.343E-5
RA-228	35000	1295	2.046E-4	2.033E-4	8.456E-4	2.033E-4	2.033E-4	.0075369	2.111E-4	5.025E-4
TOT TH			2.072E-4	2.057E-4	.0014632	2.057E-4	2.057E-4	.0152193	2.493E-4	8.198E-4
TOTAL			.0018078	.0018068	.0178408	.0018063	.0018058	.2445994	.0180036	.0158801

TABLE 4.10

ANNUAL INTAKE OF RADIONUCLIDES AND ANNUAL COMMITTED DOSE EQUIVALENT VIA INGESTION RECEIVED BY INTRUDER CONSUMING BEEF CATTLE WHICH HAD GRAZED ON THE NORTHERN SASKATCHEWAN REFERENCE TAILINGS SITE. DOSES ARE EXPRESSED IN SIEVERTS.

NUCLIDE	ACT(PCI)	ACT (BQ)	GONADS	BREAST	R MARROW	LUNGS	THYROID	ENDOSTEAL	REMAIND	EFF DE
U-238-I	9450	349.65	3.566E-8	3.262E-8	9.510E-7	3.224E-8	3.217E-8	1.413E-5	5.629E-6	2.245E-6
U-238-S	9450	349.65	8.077E-7	8.077E-7	2.378E-5	8.042E-7	8.042E-7	3.531E-4	3.388E-5	2.406E-5
U-234-I	9450	349.65	3.706E-8	3.601E-8	1.007E-6	3.601E-8	3.601E-8	1.580E-5	6.189E-6	2.469E-6
U-234-S	9450	349.65	9.056E-7	9.021E-7	2.521E-5	9.021E-7	9.021E-7	3.951E-4	3.811E-5	2.673E-5
TH-230	172368	6377.616	4.330E-6	4.337E-6	.0018431	4.337E-6	4.337E-6	.0223217	9.822E-5	9.439E-4
RA-226	738720	27332.64	.0025037	.0025064	.0163449	.0025037	.0025009	.1866819	.0028153	.0097851
PB-210	1149120	42517.44	.0053147	.0053147	.0629258	.0053147	.0053147	.9183767	.0786573	.0616503
PO-210	41040	1518.48	1.250E-4	1.250E-4	1.250E-4	1.250E-4	1.250E-4	1.250E-4	.0023081	7.805E-4
	0									
TOT U			.0079495	.0079522	.0812898	.0079494	.0079467	1.128283	.0839626	.0732153
TH-232	1724	63.788	7.974E-8	8.037E-8	9.441E-5	7.974E-8	7.718E-8	.0011801	9.377E-7	4.708E-5
TH-228	1724	63.788	1.614E-7	1.486E-7	1.231E-5	1.474E-7	1.467E-7	1.312E-4	2.462E-6	6.825E-6
RA-228	7387	273.319	4.318E-5	4.291E-5	1.785E-4	4.291E-5	4.291E-5	.0015907	4.455E-5	1.060E-4
TOT TH			4.343E-5	4.314E-5	2.852E-4	4.314E-5	4.312E-5	.0029220	4.795E-5	1.599E-4
TOTAL			.0079929	.0079953	.0815750	.0079926	.0079898	1.131205	.0840106	.0733753

TABLE 4.11

ANNUAL INTAKE OF RADIONUCLIDES AND ANNUAL COMMITTED DOSE EQUIVALENT VIA INHALATION RECEIVED BY INTRUDER CONSTRUCTING A ROAD ON THE ELLIOT LAKE REFERENCE TAILINGS SITE. DOSES ARE EXPRESSED IN SIEVERTS.

NUCLIDE	ACT(PCI)	ACT (BQ)	GONADS	BREAST	R MARROW	LUNGS	THYROID	ENDOSTEAL	REMAIND	EFF DE
U-238-Y	.84	.03108	7.52E-11	9.04E-11	2.138E-9	8.267E-6	8.48E-11	3.139E-8	2.987E-9	9.946E-7
U-238-W	.84	.03108	2.09E-10	2.09E-10	6.154E-9	4.413E-7	2.09E-10	9.138E-8	7.894E-9	5.905E-8
U-234-Y	.84	.03108	8.24E-11	8.33E-11	2.244E-9	9.262E-6	8.24E-11	3.512E-8	3.357E-9	1.113E-6
U-234-W	.84	.03108	2.34E-10	2.34E-10	6.527E-9	4.973E-7	2.34E-10	1.023E-7	8.858E-9	6.620E-8
TH-230	10	.37	6.364E-8	6.364E-8	2.586E-5	1.114E-4	6.364E-8	3.223E-4	1.658E-7	2.616E-5
RA-226	56	2.072	2.113E-7	2.113E-7	1.376E-6	3.336E-5	2.113E-7	1.573E-5	2.217E-7	4.807E-6
PB-210	68	2.516	8.001E-7	8.001E-7	9.435E-6	8.001E-7	8.001E-7	1.376E-4	1.180E-5	9.234E-6
PO-210	68	2.516	1.016E-6	1.016E-6	1.016E-6	1.834E-6	1.016E-6	1.016E-6	1.862E-5	6.391E-6
TOT U			2.092E-6	2.092E-6	3.771E-5	1.658E-4	2.092E-6	4.769E-4	3.083E-5	4.882E-5
TH-232	15	.555	3.319E-7	3.408E-7	2.226E-4	.0005217	3.324E-7	.0027695	8.381E-7	1.726E-4
TH-228	43	1.591	3.596E-7	3.691E-7	2.975E-5	.0010994	3.659E-7	3.643E-4	9.626E-7	1.468E-4
RA-228	15	.555	1.016E-7	1.021E-7	4.096E-7	4.007E-6	1.016E-7	3.613E-6	1.038E-7	7.160E-7
TOT TH			7.930E-7	8.120E-7	2.527E-4	.0016251	7.999E-7	.0031374	1.904E-6	3.202E-4
TOTAL			2.885E-6	2.904E-6	2.904E-4	.0017909	2.892E-6	.0036143	3.273E-5	3.690E-4

TABLE 4.12

ANNUAL INTAKE OF RADIONUCLIDES AND ANNUAL COMMITTED DOSE EQUIVALENT VIA INHALATION RECEIVED BY INTRUDER CONSTRUCTING A ROAD ON THE NORTHERN SASKATCHEWAN REFERENCE TAILINGS SITE. DOSES ARE EXPRESSED IN SIEVERTS.

NUCLIDE	ACT(PCI)	ACT (BQ)	GONADS	BREAST	R MARROW	LUNGS	THYROID	ENDOSTEAL	REMAIND	EFF DE
U-238-Y	20.3	.7511	1.818E-9	2.186E-9	5.168E-8	1.998E-4	2.051E-9	7.586E-7	7.218E-8	2.404E-5
U-238-W	20.3	.7511	5.040E-9	5.062E-9	1.487E-7	1.067E-5	5.040E-9	2.208E-6	1.908E-7	1.427E-6
U-234-Y	20.3	.7511	1.990E-9	2.013E-9	5.423E-8	2.238E-4	1.990E-9	8.487E-7	8.112E-8	2.689E-5
U-234-W	20.3	.7511	5.648E-9	5.648E-9	1.577E-7	1.202E-5	5.648E-9	2.471E-6	2.141E-7	1.600E-6
TH-230	221	8.177	1.406E-6	1.406E-6	5.716E-4	.0024613	1.406E-6	.0071222	3.663E-6	5.781E-4
RA-226	221	8.177	8.341E-7	8.341E-7	5.430E-6	1.316E-4	8.341E-7	6.206E-5	8.749E-7	1.897E-5
PB-210	221	8.177	2.600E-6	2.600E-6	3.066E-5	2.600E-6	2.600E-6	4.473E-4	3.835E-5	3.001E-5
PO-210	221	8.177	3.304E-6	3.304E-6	3.304E-6	5.961E-6	3.304E-6	3.304E-6	6.051E-5	2.077E-5
TOT U			8.159E-6	8.159E-6	6.114E-4	.0030478	8.159E-6	.0076411	1.040E-4	7.018E-4
TH-232	2.21	.08177	4.890E-8	5.021E-8	3.279E-5	7.686E-5	4.898E-8	4.080E-4	1.225E-7	2.543E-5
TH-228	2.21	.08177	1.848E-8	1.897E-8	1.529E-6	5.650E-5	1.881E-8	1.873E-5	4.947E-8	7.547E-6
RA-228	2.21	.08177	1.496E-8	1.505E-8	6.035E-8	5.904E-7	1.496E-8	5.323E-7	1.529E-8	1.055E-7
TOT TH			8.234E-8	8.422E-8	3.438E-5	1.340E-4	8.275E-8	4.273E-4	1.882E-7	3.308E-5
TOTAL			8.241E-6	8.243E-6	6.458E-4	.0031817	8.242E-6	.0080684	1.041E-4	7.349E-4

TABLE 4.13

ANNUAL INTAKE OF RADIONUCLIDES AND ANNUAL COMMITTED DOSE EQUIVALENT VIA INHALATION RECEIVED BY INTRUDER CAMPING ON THE ELLIOT LAKE REFERENCE TAILINGS SITE. DOSES ARE EXPRESSED IN SIEVERTS.

NUCLIDE	ACT(PCI)	ACT (BQ)	GONADS	BREAST	R MARROW	LUNGS	THYROID	ENDOSTEAL	REMAIND	EFF DE
U-238-Y	.05	.00185	4.48E-12	5.38E-12	1.27E-10	4.921E-7	5.05E-12	1.869E-9	1.78E-10	5.92E-8
U-238-W	.05	.00185	1.24E-11	1.25E-11	3.66E-10	2.627E-8	1.24E-11	5.439E-9	4.70E-10	3.515E-9
U-234-Y	.05	.00185	4.90E-12	4.96E-12	1.34E-10	5.513E-7	4.90E-12	2.091E-9	2.00E-10	6.623E-8
U-234-W	.05	.00185	1.39E-11	1.39E-11	3.89E-10	2.96E-8	1.39E-11	6.087E-9	5.27E-10	3.941E-9
TH-230	.64	.02368	4.073E-9	4.073E-9	1.655E-6	7.128E-6	4.073E-9	2.063E-5	1.061E-8	1.674E-6
RA-226	3.6	.1332	1.359E-8	1.359E-8	8.844E-8	2.145E-6	1.359E-8	1.011E-6	1.425E-8	3.090E-7
PB-210	4.4	.1628	5.177E-8	5.177E-8	6.105E-7	5.177E-8	5.177E-8	8.905E-6	7.635E-7	5.975E-7
PO-210	4.4	.1628	6.577E-8	6.577E-8	6.577E-8	1.187E-7	6.577E-8	6.577E-8	1.205E-6	4.135E-7
TOT U			1.352E-7	1.352E-7	2.421E-6	1.054E-5	1.352E-7	3.062E-5	1.994E-6	3.127E-6
TH-232	.97	.03589	2.146E-8	2.204E-8	1.439E-5	3.374E-5	2.150E-8	1.791E-4	5.419E-8	1.116E-5
TH-228	2.8	.1036	2.341E-8	2.404E-8	1.937E-6	7.159E-5	2.383E-8	2.372E-5	6.268E-8	9.562E-6
RA-228	.97	.03589	6.568E-9	6.604E-9	2.649E-8	2.591E-7	6.568E-9	2.336E-7	6.711E-9	4.630E-8
TOT TH			5.144E-8	5.268E-8	1.636E-5	1.056E-4	5.189E-8	2.030E-4	1.236E-7	2.077E-5
TOTAL			1.867E-7	1.879E-7	1.878E-5	1.161E-4	1.871E-7	2.337E-4	2.118E-6	2.390E-5

TABLE 4.14

ANNUAL INTAKE OF RADIONUCLIDES AND ANNUAL COMMITTED DOSE EQUIVALENT VIA INHALATION RECEIVED BY INTRUDER CAMPING ON THE NORTHERN SASKATCHEWAN REFERENCE TAILINGS SITE. DOSES ARE EXPRESSED IN SIEVERTS.

NUCLIDE	ACT(PCI)	ACT (BQ)	GONADS	BREAST	R MARROW	LUNGS	THYROID	ENDOSTEAL	REMAIND	EFF DE
U-238-Y	.63	.02331	5.64E-11	6.78E-11	1.604E-9	6.200E-6	6.36E-11	2.334E-8	2.240E-9	7.459E-7
U-238-W	.63	.02331	1.56E-10	1.57E-10	4.615E-9	3.310E-7	1.56E-10	6.853E-8	5.921E-9	4.429E-8
U-234-Y	.63	.02331	6.18E-11	6.25E-11	1.683E-9	6.946E-6	6.18E-11	2.634E-8	2.517E-9	8.345E-7
U-234-W	.63	.02331	1.75E-10	1.75E-10	4.895E-9	3.730E-7	1.75E-10	7.669E-8	6.643E-9	4.965E-8
TH-230	6.8	.2516	4.328E-8	4.328E-8	1.759E-5	7.573E-5	4.328E-8	2.191E-4	1.127E-7	1.779E-5
RA-226	6.8	.2516	2.566E-8	2.566E-8	1.671E-7	4.051E-6	2.566E-8	1.910E-6	2.692E-8	5.837E-7
PB-210	6.8	.2516	8.001E-8	8.001E-8	9.435E-7	8.001E-8	8.001E-8	1.376E-5	1.180E-6	9.234E-7
PO-210	6.8	.2516	1.016E-7	1.016E-7	1.016E-7	1.834E-7	1.016E-7	1.016E-7	1.862E-6	6.391E-7
TOT U			2.510E-7	2.511E-7	1.881E-5	9.390E-5	2.511E-7	2.351E-4	3.199E-6	2.161E-5
TH-232	.068	.002516	1.505E-9	1.545E-9	1.009E-6	2.365E-6	1.507E-9	1.255E-5	3.799E-9	7.825E-7
TH-228	.068	.002516	5.69E-10	5.84E-10	4.705E-8	1.739E-6	5.79E-10	5.762E-7	1.522E-9	2.322E-7
RA-228	.068	.002516	4.60E-10	4.63E-10	1.857E-9	1.817E-8	4.60E-10	1.638E-8	4.70E-10	3.246E-9
TOT TH			2.534E-9	2.591E-9	1.058E-6	4.122E-6	2.546E-9	1.315E-5	5.792E-9	1.018E-6
TOTAL			2.536E-7	2.536E-7	1.987E-5	9.802E-5	2.536E-7	2.483E-4	3.205E-6	2.263E-5

TABLE 4.15

ANNUAL INTAKE OF RADIONUCLIDES AND ANNUAL COMMITTED DOSE EQUIVALENT VIA INHALATION RECEIVED BY INTRUDER RACING AN AUTOMOBILE ON THE ELLIOT LAKE REFERENCE TAILINGS SITE. DOSES ARE EXPRESSED IN SIEVERTS.

NUCLIDE	ACT(PCI)	ACT (BQ)	GONADS	BREAST	R MARROW	LUNGS	THYROID	ENDOSTEAL	REMAIND	EFF DE
U-238-Y	.14	.00518	1.25E-11	1.51E-11	3.56E-10	1.378E-6	1.41E-11	5.232E-9	4.98E-10	1.658E-7
U-238-W	.14	.00518	3.48E-11	3.49E-11	1.026E-9	7.356E-8	3.48E-11	1.523E-8	1.316E-9	9.842E-9
U-234-Y	.14	.00518	1.37E-11	1.39E-11	3.74E-10	1.544E-6	1.37E-11	5.853E-9	5.59E-10	1.854E-7
U-234-W	.14	.00518	3.90E-11	3.90E-11	1.088E-9	8.288E-8	3.90E-11	1.704E-8	1.476E-9	1.103E-8
TH-230	1.7	.0629	1.082E-8	1.082E-8	4.397E-6	1.893E-5	1.082E-8	5.479E-5	2.818E-8	4.447E-6
RA-226	9.4	.3478	3.548E-8	3.548E-8	2.309E-7	5.600E-6	3.548E-8	2.640E-6	3.721E-8	8.069E-7
PB-210	11.4	.4218	1.341E-7	1.341E-7	1.582E-6	1.341E-7	1.341E-7	2.307E-5	1.978E-6	1.548E-6
PO-210	11.4	.4218	1.704E-7	1.704E-7	1.704E-7	3.075E-7	1.704E-7	1.704E-7	3.121E-6	1.071E-6
TOT U			3.509E-7	3.509E-7	6.383E-6	2.805E-5	3.509E-7	8.071E-5	5.169E-6	8.245E-6
TH-232	2.5	.0925	5.532E-8	5.680E-8	3.709E-5	8.695E-5	5.541E-8	4.616E-4	1.397E-7	2.877E-5
TH-228	7.4	.2738	6.188E-8	6.352E-8	5.120E-6	1.892E-4	6.297E-8	6.270E-5	1.656E-7	2.527E-5
RA-228	2.5	.0925	1.693E-8	1.702E-8	6.827E-8	6.679E-7	1.693E-8	6.022E-7	1.730E-8	1.193E-7
TOT TH			1.341E-7	1.373E-7	4.228E-5	2.768E-4	1.353E-7	5.249E-4	3.226E-7	5.416E-5
TOTAL			4.851E-7	4.883E-7	4.866E-5	3.049E-4	4.862E-7	6.056E-4	3.491E-6	6.240E-5

TABLE 4.16

ANNUAL INTAKE OF RADIONUCLIDES AND ANNUAL COMMITTED DOSE EQUIVALENT VIA INHALATION RECEIVED BY INTRUDER RACING AN AUTOMOBILE ON THE NORTHERN SASKATCHEWAN REFERENCE TAILINGS SITE. DOSES ARE EXPRESSED IN SIEVERTS.

NUCLIDE	ACT(PCI)	ACT (BQ)	GONADS	BREAST	R MARROW	LUNGS	THYROID	ENDOSTEAL	REMAIND	EFF DE
U-238-Y	.25	.00925	2.24E-11	2.69E-11	6.36E-10	2.461E-6	2.53E-11	9.343E-9	8.89E-10	2.96E-7
U-238-W	.25	.00925	6.21E-11	6.23E-11	1.832E-9	1.314E-7	6.21E-11	2.720E-8	2.350E-9	1.758E-8
U-234-Y	.25	.00925	2.45E-11	2.48E-11	6.68E-10	2.757E-6	2.45E-11	1.045E-8	9.99E-10	3.312E-7
U-234-W	.25	.00925	6.96E-11	6.96E-11	1.943E-9	1.48E-7	6.96E-11	3.043E-8	2.636E-9	1.970E-8
TH-230	2.7	.0999	1.718E-8	1.718E-8	6.983E-6	3.007E-5	1.718E-8	8.701E-5	4.476E-8	7.063E-6
RA-226	2.7	.0999	1.019E-8	1.019E-8	6.633E-8	1.608E-6	1.019E-8	7.582E-7	1.069E-8	2.318E-7
PB-210	2.7	.0999	3.177E-8	3.177E-8	3.746E-7	3.177E-8	3.177E-8	5.465E-6	4.685E-7	3.666E-7
PO-210	2.7	.0999	4.036E-8	4.036E-8	4.036E-8	7.283E-8	4.036E-8	4.036E-8	7.393E-7	2.537E-7
TOT U			9.968E-8	9.968E-8	7.469E-6	3.729E-5	9.968E-8	9.335E-5	1.270E-6	3.580E-6
TH-232	.027	.000999	5.97E-10	6.13E-10	4.906E-7	9.391E-7	5.98E-10	4.985E-6	1.508E-9	3.107E-7
TH-228	.027	.000999	2.26E-10	2.32E-10	1.868E-8	6.903E-7	2.30E-10	2.288E-7	6.04E-10	9.221E-8
RA-228	.027	.000999	1.83E-10	1.84E-10	7.37E-10	7.213E-9	1.83E-10	6.503E-9	1.87E-10	1.289E-9
TOT TH			1.006E-9	1.029E-9	4.200E-7	1.637E-6	1.011E-9	5.220E-6	2.300E-9	4.042E-7
TOTAL			1.007E-7	1.007E-7	7.889E-6	3.892E-5	1.007E-7	9.857E-5	1.272E-6	8.984E-6

TABLE 4.17

ANNUAL COMMITTED DOSE EQUIVALENT AND ANNUAL SKIN DOSE RECEIVED BY INTRUDER SWIMMING IN A POND ON THE ELLIOT LAKE REFERENCE TAILINGS SITE. DOSES ARE EXPRESSED IN MILLISIEVERTS. CONCENTRATION OF RADIONUUCLIDES IN POND WATER EXPRESSED IN PCI/L OR BQ/L.

NUCLIDE	ACT PCI	ACT BQ	EDE	SKIN
U-238	20	.74	.000074	.00174
U-234	20	.74	.0000046	.0000056
TH-230	20	.74	.0000044	.0000054
RA-226	20	.74	.0052	.008
PB-210	20	.74	.0000138	.00058
PO-210	20	.74	2.6E-8	3.2E-8
TOTAL U			.0052968	.0103310
TH-232	2	.074	3.6E-7	4.6E-7
RA-228	2	.074	.00028	.00042
TH-228	2	.074	.00046	.00074
TOTAL TH			7.404E-4	.0011605
TOTAL			.0060372	.0114915

TABLE 4.18

ANNUAL COMMITTED DOSE EQUIVALENT AND ANNUAL SKIN DOSE RECEIVED BY INTRUDER SWIMMING IN A POND ON THE NORTHERN SASKATCHEWAN REFERENCE TAILINGS SITE. DOSES ARE EXPRESSED IN MILLISIEVERTS. CONCENTRATION OF RADIONUUCLIDES IN POND WATER EXPRESSED IN PCI/L OR BQ/L.

NUCLIDE	ACT PCI	ACT BQ	EDE	SKIN
U-238	540	19.98	.001998	.04698
U-234	540	19.98	.0001242	.0001512
TH-230	540	19.98	.0001188	.0001458
RA-226	540	19.98	.1404	.216
PB-210	540	19.98	.0003726	.01586
PO-210	540	19.98	7.02E-7	8.64E-7
TOTAL U			.1430143	.2789379
TH-232	5.4	.1998	9.72E-7	1.242E-6
RA-228	5.4	.1998	.000756	.001134
TH-228	5.4	.1998	.001242	.001998
TOTAL TH			.0019990	.0031332
TOTAL			.1450133	.2820711

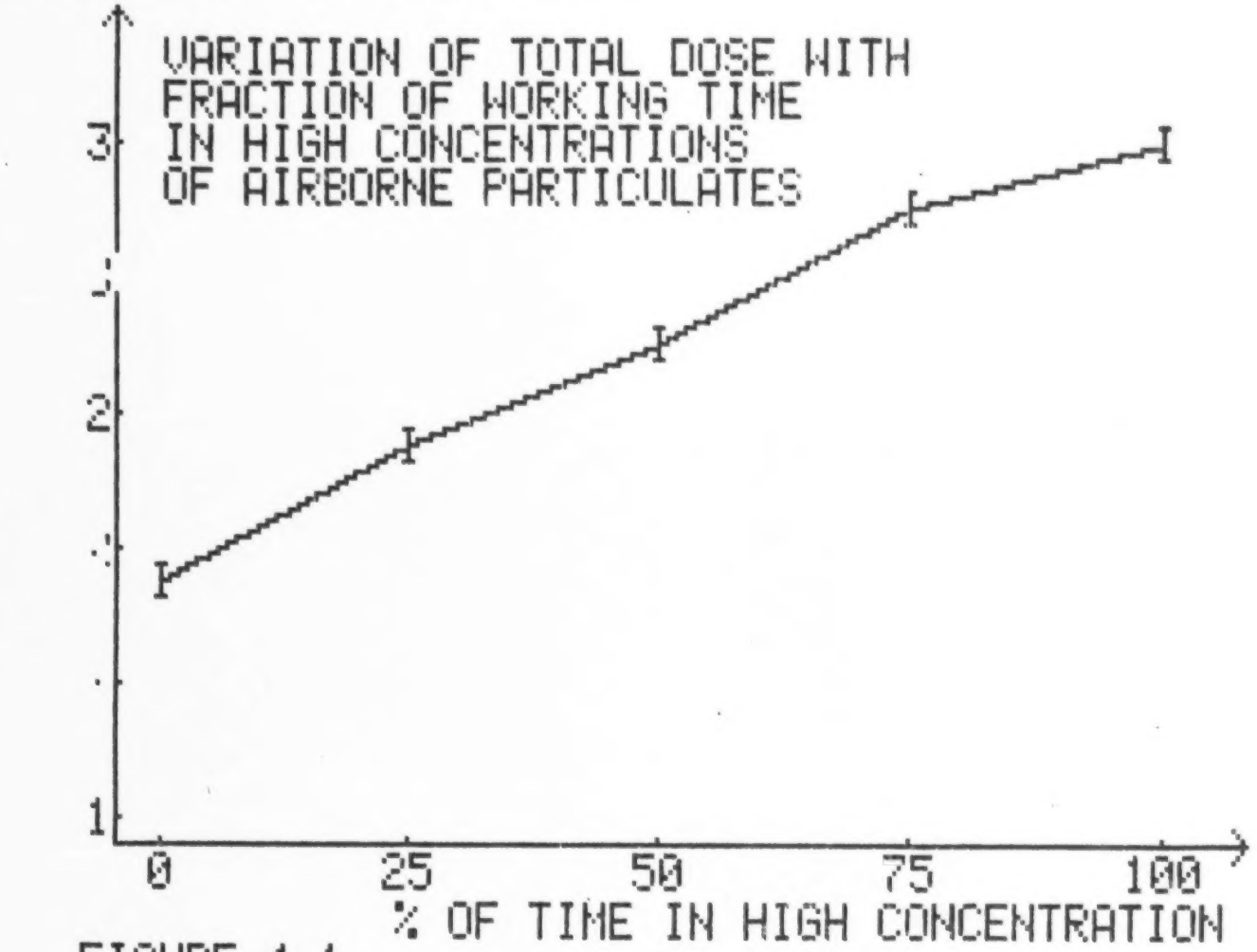
TOTAL DOSE (MILLISIEVERT)
VARIATION OF TOTAL DOSE WITH
FRACTION OF WORKING TIME
IN HIGH CONCENTRATIONS
OF AIRBORNE PARTICULATES
3
2
1
0
25
50
75
100
% OF TIME IN HIGH CONCENTRATION

FIGURE 4.1

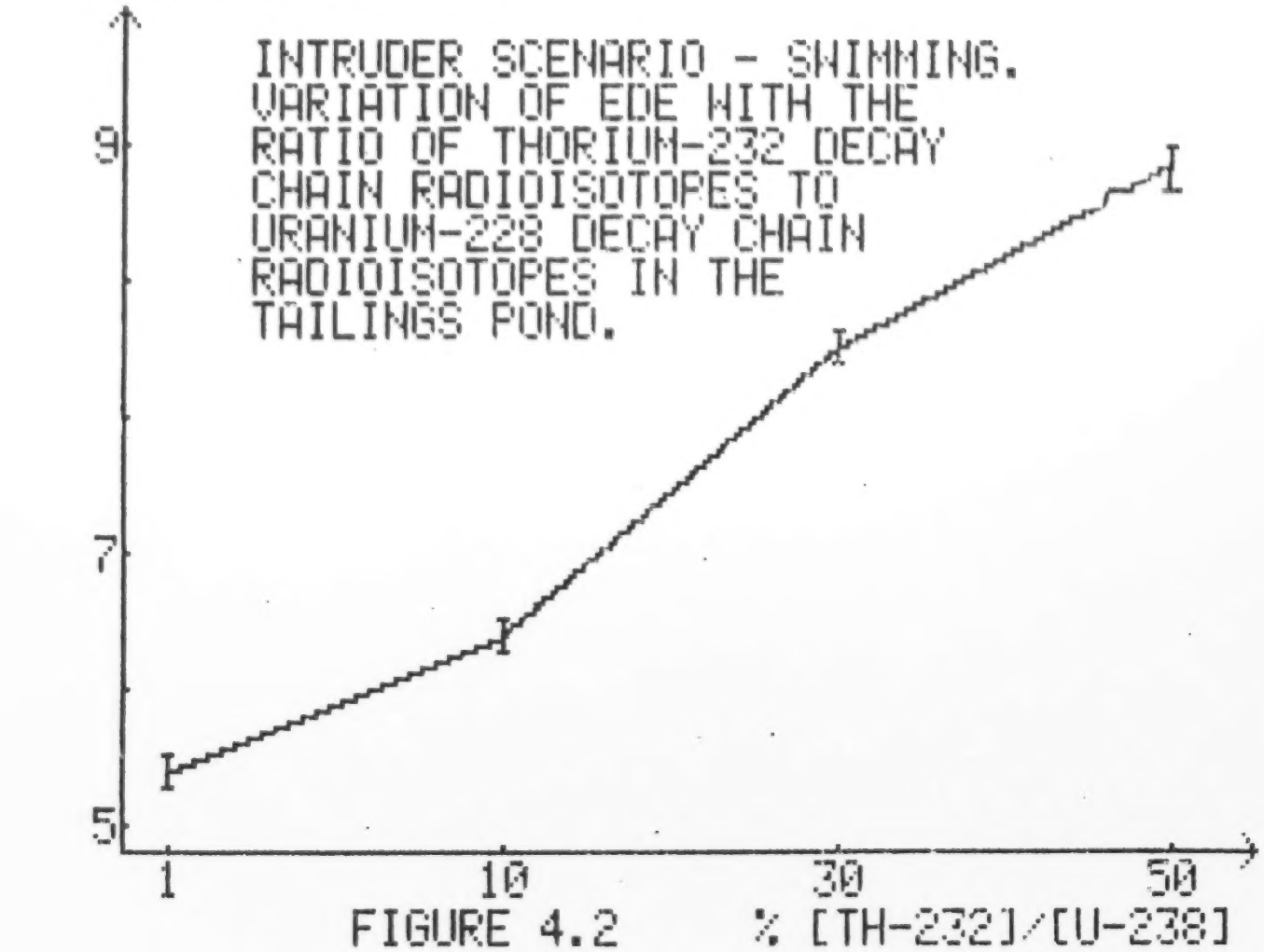
DOSE (MICROSIEVERTS)
INTRUDER SCENARIO - SWIMMING.
VARIATION OF EDE WITH THE
RATIO OF THORIUM-232 DECAY
CHAIN RADIOISOTOPES TO
URANIUM-238 DECAY CHAIN
RADIOISOTOPES IN THE
TAILINGS POND.
9
7
5
1
10
30
50
% [TH-232]/[U-238]

FIGURE 4.2

5.0 RECOMMENDATIONS

Development of Reference Tailings Sites

An appropriate reference site can be characterized for the Elliot Lake mining region and in fact has been done so by Beak (1983). However, given the differences in tailings management schemes between the existing northern Saskatchewan sites, the sparcity of data from these sites, and the uncertainties remaining in the disposal concepts, incorporation of parameters from all existing sites into the northern Saskatchewan reference site was not considered feasible at this time and the reference site for northern Saskatchewan was based on the Rabbit Lake site. It is recommended that the parameters of the northern Saskatchewan reference site be reevaluated when site specific data become reasonably adequate. Furthermore, it does not appear meaningful to develop one generic site which would be applicable to both Elliot Lake and northern Saskatchewan. However, it is appropriate to apply the methodology utilized in this study to land/shallow lake tailings management sites in both the Elliot Lake and the northern Saskatchewan mining regions.

Radioisotope Soil To Plant Transfer Parameters

The doses resulting from the agricultural scenarios depend strongly on the transfer parameters from soil to plant. Also, the data for radium-226, uranium, and lead-210 from Kalin (1985) yield significantly different transfer parameters than are reported in the standard literature such as in the U.S. Nuclear Regulatory Commission document, (NUREG-0706,1980). Confirmation of the general applicability of Kalin's data should be established. In addition, experimental data which would provide soil-to-plant transfer parameters for the thorium and polonium isotopes are required.

Assessment of Consequences of Ingestion of Toxic Chemicals

This study was limited to the determining the consequences, in terms of radiation doses to the intruder, resulting from various scenarios. However, in addition to the uptake of radioactivity, the intruder would be subjected to exposure to toxic chemicals, primarily through ingestion but possibly also through inhalation. In order to determine the total risk to the intruder, the hazards associated with exposure to toxic chemicals should be evaluated.

REFERENCES

Beak, 1983.
An Approach to the Calculation of Dose Commitment Arising from Different Methods for the Long-Term Management of Uranium Mill Tailings. Summary Report. Atomic Energy Control Board Report INFO-0097.

Beak, 1983a
An Approach to the Calculation of Dose Commitment Arising From Different Methods for the Long-Term Management of Uranium Mill Tailings Through Aquatic Pathways, Technical Appendix. Atomic Energy Control Board Report INFO-0097.

Beak, 1983b
Atmospheric Dispersion of Radionuclides fromUranium Mill Tailings Disposal Sites. Technical Appendix. Atomic Energy Control Board Report INFO-0097.

Bigu, 1984.
Radon Gas Concentration, Surface Radon Flux and Other Radiation Variables from Uranium Mine Tailings Areas. Bigu, J., Grenier, M., Dave, N., Lim, T., Chakravatti, J.L. Presented at the Sixth Symposium on Uranium Mill Tailings Management, Fort Collins, Colorado.

Bigu, 1984a.

Study of Radon Gas Concentration, Surface Radon Flux and Other Radiation Variables from Uranium Mine Tailings Areas. Bigu, J., Grenier, M., Dave, N.K., Lim, T.P., Chakravatti, J.L. Uranium 1.

CEC, 1979.
Methodology for Evaluating the Radiological Consequences of Radioactive Effluents Released in Normal Operations. Commission of European Communities Doc. No. V/.3865/79 cited in Beak (1983b).

Chambers, 1982.
Overview of Uranium Tailings Management Practice. Chambers, D.B., Knapp, R.A., Ibbotson, B.G., Lowe, L.M. Presented at: Canadian Nuclear Society, International Conference on Radioactive Waste Management, Winnipeg, Manitoba.

DSMA, 1983.
Review of Existing Instrumentation and Evaluation of Possibilities for Research and Development of Instrumentaion to Determine Future Levels of Radon at a Proposed Building Site. DSMA Atcon Ltd. Atomic Energy Control Board Report, INFO-0096.

Eaton, 1984.

Understanding Radon Transport Into Houses. Eaton, R.S., Scott, A.G. Radiation Protection Dosimetry, Vol 7, No. 1-4.

Filion, 1985.
Private Communication. Filion, M.P. Elderado Resources Limited.

Goldsmith, 1978.
Guidelines for Cleanup of Uranium Tailings from Inactive Mills. Goldsmith, W.A., Haywood, F.F., Jacobs, D.G., Presented at the Ninth Midyear Health Physics Topical Symposium on Operational Health Physics.

Haywood, 1977
Assessment of Radiological Impact of the Inactive Uranium-Mill Tailings Pile at Salt Lake City, Utah. Haywood, F.F., Goldsmith, W.A., Perdue, P.T., Fox, W.F., Shinpaugh, W.H. Oak Rirge National Laboratory Report ORNL/TM-5251.

Hunt, 1984.
Simple Models for Prediction of External Radiation Exposure from Aquatic Pathways. Hunt, G.J. Radiation Protection Dosimetry, Vol. 8, No.4.

ICRP-23, 1975.
Report of the Task Group on Reference Man. International Commission on Radiological Protection Publication 23, Pergamon Press.

ICRP-26, 1977.
Recommendations of the International Commission on Radiological Protection. ICRP Publication 26, Pergamon Press.

ICRP-39, 1984.
Principles for Limiting Exposures of the Public to Natural Sources of Radiation. Annals of the ICRP. ICRP Publication 39, Pergamon Press.

John, 1985.
Private Communication. John, R. Canada Centre for Mineral and Energy Technology, Energy, Mines and Rsources, Canada.

Kalkwarf, 1979.
Solubility Classification of Airborne Products from Uranium Ores and Tailings Piles. Kalkwarf, D.R. NUREG/CR-0530, PNL-2870.

Kocher, 1979.
Dose Rate Conversion Factors for External Exposures to Photon and Electron Radiation from Radionuclides Occurring in Routine Releases from Nuclear Fuel Cycle Facilities. Kocher, D.C. NUREG/CR-0494.

Kocher, 1981.
Electron Dose-Rate Conversion Factors for External Exposure of the Skin. Kocher, D.C., Eckerman, K.F. Health Physics, Volume

40, No. 4.

Kocher, 1985.
Dose-Rate Conversion Factors for External Exposure to Photon Emitters in Soil. Kocher, D.C., Sjoreen, A.L. Health Physics, Vol. 48, No. 2.

Larson, 1982.
Uranium Mine Waste Management in Saskatchewan. Larson, D.W., Robertson, B.E., Woods, R.J. Presented at: Canadian Nuclear Sociey, International Conference on Radioactive Waste Management, Winnipeg, Manitoba.

Lauridsen, 1983.
Shielding Factors for Vehicles to Gamma Radiation from Activity Deposited on Structures and Ground Surfaces. Lauridsen, B., Jensen, P.H. Health Physics, Vol. 45, No. 6.

Leach, 1982.
A Study of Radiation Parameters in an Open-Pit Mine. Leach, V.A., Lokan, K.H., Martin, L.J. Health Physics Vol. 43, No. 3.

Leddicotte, 1978.
Suggested Concentration Limits for Shallow-Land Burial of Radionuclides. Leddicotte, G.W., Tarnuzzer, E.C., Rodger, W.A., Frendberg, R.L., Morton, H.W., Presented at Symposium on Waste Management and Fuel Cycles '78, Tucson, Arizona.

Lim, 1978.
Measurement of Radium-226 in Water from Test Wells in a Uranium Tailings Area. Lim, T.P., Dave, N.K. Canada Centre for Mineral and Energy Technology Report MRP/MRL 78-70 (TR).

Lindell, 1984.
A Radon Control Programme in Theory and Practice. Lindell, B. Radiation Protection Dosimetry, Vol. 7, No. 1-4.

MacLaren, 1977.
Environmental Assessment of the Proposed Elliot Lake Uranium Mines Expansion, Volume 1, Background Information. J.F. MacLaren Limited.

MacLaren, 1978.
Environmental Assessment of the Proposed Elliot Lake Uranium Mines Expansion, Addendum 1. J. F. MacLaren Limited.

MacLaren, 1982.
The Development of an Assessment Methodology for the Near Surface Disposal of Radioactive Waste.
MacLaren Engineers, Senes Consultants Limited.

Moffett, 1977.
Radiological Investigations of an Abandoned Uranium Tailings Area. Moffett, D., Tellier, M. Canada Centre for Mineral and Energy Technology, Report MRP/MRL 77 - 54(J).

Murray, 1981.
Particle Size Distribution of Uranium Tailings Core Samples. Murray, D.R., Turcotte, M. Canada Centre for Mineral and Energy Technology, Report MRP/MRL 81-13(TR).

Pun, 1985.
Personal Communication. Pun, M. Energy, Mines and Resources, Canada.

Roessler, 1978.
The Effect of Mining and Land Reclamation on the Radiological Characteristics of the Terrestrial Environment of Florida's Phosphate Regions. Roessler, C.E., Kautz, R., Bolch, W.E. Jr., Wethington, J.A. Jr., Symposium: Natural Radiation Environment III, Houston, Texas.

Schaiger, K.J., 1974.
Analysis of Radiation Exposures on or Near Uranium Mill Tailings Piles. Radiation Data and Reports, 15, 411-425.

Slade, 1968.
Meteorology and Atomic Energy. Slade, D.S. U.S. Atomic Energy Commission.

Swedjemark, 1981.
Buildings with Enhanced Radioactivity in Sweden. Swedjemark, G.A., Presented at the Second Special Symposium on Natural Radiation Environment, Bombay, India.

Swedjemark, 1983.
The Equilibrium Factor F. Swedjemark, G.A., Health Physics, Vol. 45, No. 2.

Till, 1983.
Radiological Asessment. A Textbook on Environmental Dose Analysis. Till, J.E., Meyer, H.R., NUREG/CR-3332, ORNL-5968.

Tracy, 1983.
Transfer of Ra-226, Pb-210, and Uranium from Soil to Garden Produce: Assessment of Risk. Tracy, B.L., Prantl, F.A., Quinn, J.M. Health Physics Vol. 44, No. 5.

USEPA, 1977.
Compilation of Air Pollutant Emission Factors. Third Edition. Report AP-42-ED-3-PTS-A/B.

USNRC, 1975.
Reactor Safety Study; An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants. Appendix 6: Calculation of Reactor Accident Consequences. U.S. Nuclear Regulatory Commission, Report NUREG 75/014, WASH-1400.

Wicke, 1984.
Exposure of the Population to Radon Daughters - Problems Associated with the Assessment of the Annual Dose. Wicke, A. Radiation Protection Dosimetry, Vol. 7, No. 1-4.